SLAC – PUB – 4369
July 1987
(T/E)

SEARCH FOR CHARGED HIGGS BOSONS AT SSC

HANS-UNO BENGTSSON AND HIROAKI YAMAMOTO
University of California at Los Angeles
Los Angeles, California 90024

SACHIO KOMAMIYA*
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

We examine the possibility of finding charged Higgs bosons ($H^{\pm}$) at the SSC. The charged Higgs boson is produced with a top quark via a gluon + bottom quark interaction ($g + b \rightarrow H + t$). For the two Higgs doublet models, $H^{\pm}$ decays predominantly into $t + b$. Since the background from QCD processes will be very severe for this decay mode, we studied the $H^{\pm} \rightarrow \tau + \nu$ decay mode. Even for this mode, background from the processes $pp \rightarrow W + t + spectators \rightarrow \ell + \nu_{\ell} + t + spectators$ will be very high. In the two Higgs doublet models, it is very difficult to extract the charged Higgs signal for reasonable values of the ratio of the two vacuum expectation values ($\tan \beta = v_1/v_2$).

Talk presented at the Workshop: From Colliders to Supercolliders,
Madison, Wisconsin, May 11–22, 1987.

⋆ Work supported by the Department of Energy, contract DE–AC03–76SF00515.

1. Introduction

1.1 CHARGED HIGGS BOSONS IN THE TWO DOUBLET MODELS

If the Higgs sector is non-minimal, in general, there will be physical charged Higgs bosons. The minimal extension of the Higgs sector is to add another SU(2) Higgs doublet:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^o \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^o \end{pmatrix},$$

where ϕ_1^+, ϕ_1^o, ϕ_2^+ and ϕ_2^o are complex fields. Therefore there are initially eight fields. The vacuum expectation values (VEV's) are

$$< \phi_1 >= \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \qquad < \phi_2 >= \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}.$$

Assuming CP non-violation, the relative phase between the two vacuum expectation values is zero.

The quadratic sum of the VEV is equal to the VEV squared (v^2) of the standard Higgs boson, hence $M_{W_\pm} = g \cdot v/2 = g \cdot \sqrt{(v_1^2 + v_2^2)}/2$.

Since the ρ parameter ($\rho = \frac{M_W^2}{M_Z^2 cos^2\theta_w}$) is experimentally consistent with unity, ($\rho = 1.006 \pm 0.008$) [1] the structure of the Higgs multiplet is likely to be SU(2) doublets (not triplets, etc). At least two Higgs doublets are necessary for most of the supersymmetric models [2] and models with axion(s) need at least two Higgs doublets [3]. Therefore, for a working hypothesis, the two SU(2) doublet model is assumed in this report. For the two SU(2) doublet models, there are three physical neutral Higgs bosons (H_1^o, H_2^o, H_3^o) and two charged Higgs bosons (H^+ and H^-). Originally there are four neutral and four charged fields but one neutral field is absorbed to give mass to the Z^o and two charged fields to $W^\pm$ by the Higgs mechanism. The mass eigenstates of the physical Higgs bosons can be mixtures of the weak eigenstates. There are two mixing angles for two Higgs doublets since the charged and neutral sector do not mix. One of the mixing angles is related to the ratio of the vacuum expectation values. In general, the physical Higgs bosons in the two doublet model are given by

$$H^{\pm} = -\phi_1^{\pm} \sin\beta + \phi_2^{\pm} \cos\beta,$$
$$H_1^o = \sqrt{2}[(Re\phi_1^o - v_1)\cos\alpha + (Re\phi_2^o - v_2)\sin\alpha],$$
$$H_2^o = \sqrt{2}[-(Re\phi_1^o - v_1)\sin\alpha + (Re\phi_2^o - v_2)\cos\alpha],$$
$$H_3^o = \sqrt{2}[-Im\phi_1^o \sin\beta + Im\phi_2^o \cos\beta].$$

The mixing angle β is defined by $\tan\beta = \frac{v_2}{v_1}$. The other angle α is also an arbitrary parameter. The recipe to obtain the above linear combinations is given elsewhere [4]. Among the neutral Higgs bosons, H_3^o is a pseudoscalar and the other two are scalars, if their parities are defined through the couplings with fermions. To be more precise, H_3^o is CP-odd state and the other neutrals (H_1^o and H_2^o) are CP-even states. The interactions of Higgs bosons with fermions can be determined from the fermion mass term in the Lagrangian. The couplings are different from model to model and depend on which Higgs is more responsible for which fermion mass. An important constraint on the Higgs couplings is that flavor changing neutral currents (FCNC) cannot be induced by the neutral Higgs bosons (or at least the FCNC should be suppressed within the experimentally allowed level). FCNC from the neutral Higgs sector are absent if each fermion is allowed to couple only with one of the two Higgs doublets (only with ϕ_1^o or only with ϕ_2^o).

2. Phenomenologies of the charged Higgs bosons at SSC

2.1 PRODUCTION

A charged Higgs boson is produced in pp collision at SSC in conjunction with a top quark via gluon + bottom quark interaction ($g + b \rightarrow H + t$) as shown in Fig.1[5].

Note that calculations based on the bt-fusion processes assuming the top distribution function in the proton (Fig.2), which is a poorer approximation than the above calculation, give larger cross section[5].

The cross section is typically $O(10)pb$ for the charged Higgs boson mass of $O(300)$ GeV, $v_2/v_1 = O(1)$ and $M_t = 40\ GeV$.

In general, the charged Higgs boson cannot be produced by WZ-fusion processes for any Higgs doublet models since HZW-couping is forbidden, whereas the standard neutral Higgs boson can be predominantly produced via WW- or ZZ- fusions.

2.2 DECAY

Since the WZH coupling is forbidden in general for the doublet models, the charged Higgs boson decays dominantly into the heaviest possible SU(2) doublet fermion pair. Hence the most probable decay mode is $H^- \to \bar{t}b$. It is, however, very difficult to look for this decay mode, because the QCD background is very severe. To consider this mode, we need B-meson tagging by using its long lifetime ($O(10^{-12}$ *sec*) and tagging of the isolated leptons from top quark semileptonic decay. Since the impact parameter distribution of the decay products is Lorentz invariant, the higher B-meson momentum does not help to look for the secondary vertex. To tag B-meson's, a vertex detector with a reasonably good position resolution and a fast response should be installed very close to the beam pipe and/or the direct B-decay should be seen in the detector (The flight length of a 150 *GeV* B-meson is about 1 *cm*). Even at the SLC it is not easy to look for B-mesons with large efficiency, and the efficiency might be much less at SSC because of the less clean environment and the pile up effects of the signals. Because of the above reasons we have not considered the $H^- \to \bar{t}b$ decay mode.

The cleaner decay mode is $H^- \to \tau^- + \nu_\tau$. Although the decay branching fraction is expected to be small, it is worth studying this mode.

2.3 MODEL DEPENDENCE OF THE EVENT RATE

In the two doublet models, each fermion is required to couple only to one of the Higgs doublets, in order to avoid tree level flavor changing neutral currents (FCNC) while diagonalizing the quark mass matrix. In supersymmetric two doublet models, all the fermions with weak isospin $I_W = 1/2$ couple only to ϕ_1 and those with $I_W = -1/2$ couple only to ϕ_2. For this model, the cross section and the decay branching fractions are

$$\sigma(g + b \to H + t) \propto M_t^2 \cot^2\beta + M_b^2 \tan^2\beta$$

$$Br(H \to \tau + \nu) \propto \frac{M_\tau^2 \tan^2\beta}{3(M_t^2 \cot^2\beta + M_b^2 \tan^2\beta)}$$

hence $\sigma(g + b \to H + t) \cdot Br(H \to \tau\nu) \propto \tan^2\beta$, where $\tan\beta = v_2/v_1$. Therefore the event rate depends on the ratio of the two vacuum expectation values.

For $\tan\beta = 1$, $M_t = 40\ GeV$ and the integrated luminosity of $10^{40} cm^{-2}$ the total expected number of $H^{\pm}$ is $\sigma(pp \rightarrow tH + spectators) \cdot \int Ldt \approx 170,000$, and the number of $H \rightarrow \tau + \nu$ decay is $\sigma(pp \rightarrow Ht + spectators) \cdot Br(H \rightarrow \tau\nu) \cdot \int Ldt \approx 115$.

The number cannot be arbitrarily large since the parameter $\tan\beta$ is experimentally limited by heavy quark decay rates, $K^o - \bar{K}^o$ mixing, etc[6]. For example $\tan\beta < O(100)$ is required, otherwise b-quark decays into $c\tau^-\bar{\nu}_\tau$ via H^- with a large fraction, for a $M_{H^\pm}$ of about 300 GeV.

2.4 MONTE CARLO EVENT GENERATOR

The charged Higgs boson productions at SSC and the decay processes are simulated in the frame work of the Lund PYTHIA event generator[7]. The production cross section was taken from the calculation by Gunion et at.[5]. The initial and final gluon radiations are included by the QCD leading-log approximation with coherent gluon interference effects.

3. Monte Carlo studies

3.1 EVENT TOPOLOGY OF THE SIGNAL ($pp \rightarrow Ht + spectators \rightarrow \tau\nu_\tau + t + spectators$)

The following event signatures are expected for the process $pp \rightarrow Ht + spectators \rightarrow \tau\nu t + spectators$:

(1) isolated high P_T charged particle accompanied by ≥ 0 π^o's (they come from the tau decay),

(2) large missing momentum due to ν_τ ($p_T < M_H/2$),

(3) a relatively isolated lepton from the semileptonic decay of the top-quark can be seen.

3.2 BACKGROUND

(1) QCD processes:

QCD processes may fake any topology since the cross section is very large. For $p_{T,jet} > 40GeV$, the cross section is about 0.32 mb.

(2) $pp \rightarrow W^* + spectators \rightarrow \ell + \nu + spectators$:

This cross section is also large ($\approx 10\mu b$) but most of the cross section is for the real W production. The isolated lepton (from top quark) is not expected for this process.

(3) $pp \rightarrow W + Z + spectators$, $W \rightarrow \ell\nu$ and $Z \rightarrow \nu\nu$:

The p_T distribution of the ℓ might be softer than the "τ" from $H^{\pm}$ decay. The cross section is relatively small ($\approx 2.5nb$).

(4) $pp \rightarrow W + q + spectators$ or $pp \rightarrow W + g + spectators$, where $W \rightarrow \ell\nu$

The cross section is large ($\approx 44\mu b$). The most severe background is from the process $pp \rightarrow W + t + spectators$, where $W \rightarrow \ell\nu$. The event topology is identical to that for the signal.

3.3 POSSIBLE EVENT SELECTION CRITERIA

Considering the event shape of the charged Higgs events and topology of possible background events, the following experimental cuts are proposed.

(1) High p_T "τ" selection

The charged particle with highest p_T is defined as the "τ" candidate. No other charged particles are within a narrow cone around the particle. The narrow cone is defined by the half angle ψ satisfying $cos\psi = 0.999$.

(2) High p_T condition of the "τ"

The "τ" candidate can be associated with γ's (π^o's). The charged particle momentum and the photon momenta in the narrow cone are summed vectorially. The resultant $|\vec{p}_T(\text{"}\tau\text{"})|$ must exceed 100 GeV and $|\eta(\text{"}\tau\text{"})| < 1.5$.

(3) Isolation condition of the "τ"

Around the narrow cone ("τ"), a broader region is defined by $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.8$. The E_T sum in the region (excluding the region in the narrow cone) must be smaller than 20 GeV. This imposes that the "τ" must be isolated.

(4) Large missing p_T

The missing $|\vec{p}_T|$ of the event must exceed 50 % of the $|\vec{p}_T(\text{"}\tau\text{"})|$.

(5) Stiff lepton from the top decay

The event should have an additional lepton (e or μ) with $p_T > 5$ GeV, $5° < \theta_{lepton} < 175°$ and opposite sign charge to the observed "τ". Since the lepton is supposed to come from the top quark, it is required to be isolated from the nearest reconstructed jet. The isolation condition is given by $\sqrt{2 \cdot p_\ell (1 - \cos\theta_{\ell j})} > 0.8$, where p_ℓ is the momentum of the lepton and $\theta_{\ell j}$ is the angle between the lepton and the nearest reconstructed jet which is found by the Lund cluster algorithm[8].

In the Fig.3, the p_T distribution of the "τ" candidate is shown for the charged Higgs events and for the background processes. Note that the distributions are not normalized with the same luminosity. Since not all the energy of the tau is observable, the shape of the p_T distribution for the $H^{\pm} + t$ events is a sort of Jacobian peak which is not very sharp. In the psuedorapidity distributions for the "τ"s, most of the background events peak at the large $|\eta|$, whereas the signal is mostly in the small $|\eta|$ region.

The lepton isolation observable $\rho = \sqrt{2 \cdot p_\ell \cdot (1 - \cos\theta_{\ell j})}$* for the leptons from the direct decays of the top quark and for the leptons from b and c quarks is shown in Fig.4. The distribution for the light quarks is peaked at $\rho \approx 0$, whereas the leptons from the top have a wider distribution. The cut we chose is indicated in the figure.

3.4 SUMMARY OF THE MONTE CARLO STUDIES

A summary of the numbers of events left after all the cuts is listed in Table 1. The numbers are based on the integrated luminosity of $10^{40} cm^{-2}$. The most severe background is from process (4) including $pp \to W + t + spectators$ with $W \to \ell + \nu$ since the topology is similar to that for the signal.

In conclusion, although the production rate of the charged Higgs boson is fairly large, it is very difficult to isolate the signal from the background. In our Monte Carlo studies, energy and angular smearings are not taken into account. If we considered a realistic detector with faked leptons and with resonable detection efficiencies for the leptons, the situation would be much worse.

* This variable is proposed by Tim Barklow to select top semileptonic decay at SLC energies[9].

3.5 Comments on isolated high p_T trigger

It is essential to study whether the trigger rate of these events is reasonably low with a reasonably large efficiency for the signal. For a simple minded "high p_T trigger" ($p_{T,jet} > 80\ GeV$), the rate is about 10,000 Hz, which is obviously too high.

To reduce the rate, a simple isolated high p_T trigger was studied. A fine-segmented calorimeter with the covered pseudorapidity range $-1.5 < \eta < 1.5$ with a size of the calorimeter cell of $\Delta\phi = 1°$ and $\Delta\eta = 0.01$ is assumed. The calorimeter is subdivided into 48 segments, each of which consists of 45 (in ϕ) $\times 50$ (in η) cells.

The trigger condition is that the $p_T(cell)$ has to exceed 80 GeV and no other cells with $p_T > 15\ GeV$ within that segment. The trigger efficiency of the Ht events is about 15 % and the trigger rate is less than 50 Hz for the QCD processes (the number is limited by the Monte Carlo statistics).

3.6 Comments on the charged Higgs boson searches at $O(\frac{1}{2}-1)\ TeV$ e^+e^- colliders

In principle, new particles without color are easier to look for at e^+e^- colliders than at hadron colliders. It is, however, not easy to construct a $O(1)TeV$ e^+e^- collider with high luminosity ($10^{34}cm^{-2}$) by the present technologies. If such a machine were to be built, it would not be difficult to look for any charged particles. It is very important to study the Higgs production (charged or neutral) both at hadron colliders and at e^+e^- machines, since the number of events expected might be larger at hadron colliders, but the background situation is far better at e^+e^- colliders.

The charged Higgs pair production cross section at e^+e^- colliders normalized by the muon pair first order QED cross section $R(H^+H^-) = \sigma(H^+H^-)/\sigma(\mu^+\mu^-)$ is slightly larger than $0.25 \cdot \beta^3$, since the contribution of the process via a virtual photon dominates over the Z^o process in the $O(0.5-1)TeV$ region. The background from $e^+e^- \to W^+W^-$ and $e^+e^- \to Z^oZ^o$ can be easily eliminated by a polar angle cut and an invariant mass cut. By reconstructing the four jets from $e^+e^- \to H^+H^- \to t\bar{b} + b\bar{t}$, the mass peak can be found over the smooth background from higher order QCD processes if the charged Higgs mass is not too close to M_Z or M_W. If the integrated luminosity of $10^{40}cm^{-2}$ and the beamstrahlung effects are not too severe, we can obtain about 100 events for 150 GeV Higgs boson over a smooth background. The

S/N ratio is typically larger than unity. If we can use the B-tagging technique, by looking for large impact parameter charged particles, the background will be greatly reduced. The size of the beam spot should be less than one micron, hence the impact parameter can be measured better than at PEP/PETRA and even better than at SLC, if we can install a vertex detector close to the beam.

4. Conclusions and Future Studies

It is very difficult to find charged Higgs bosons with mass of $O(300)GeV$ at SSC. In the two Higgs doublet models, it is almost impossible to find the charged Higgs boson by detecting the decay mode of $H^+ \to \tau^+\nu_\tau$ for reasonable values of the two vacuum expectation values since the background from the process $pp \to W + t + spectators$ with $W \to \ell + \nu$ is much larger. The QCD background is hard to estimate because a large number of Monte Carlo events have to be generated to study the tail of jet fragmentation.

Although the result of our study was negative, we have developed a number of tricks to enhance events with some distinctive topologies. For example, isolated high "p_T" particle selection, tagging the leptons from top semileptonic decays etc. These criteria can be used to look for new particles with much larger cross sections: namely particles with color.

Acknowledgements

We would like to thank the local organizing committee for the warm hospitality and for providing us an excellent atomosphere to study the phenomenologies at future colliders, especially at SSC. We appreciate the extensive discussions with J.F. Gunion and H.E. Haber on the theoritical and phenomenological aspects of this work.

REFERENCES

[1] Altarelli,G., Proc. of Int. Conf. on High Energy Physics, Berkeley (1986) p119

[2] Haber,H.E. and Kane,G.L., Phys. Reports, 117(1984)279

[3] Peccei,R.D. and Quinn,H.R., Phys Rev. Lett., 38(1977)1440;
Phys. Rev., D16(1977)1791
Bardeen,W.A. and Tye,S.-H.H. Phys. Lett., 74B(1978)229
Bardeen,W.A., Tye,S.-H.H., and Vermaseren,J.A.M., Phys. Lett., 76B(1978)580

[4] Haber,H.E., Kane,G.L., and Sterling,T., Nucl. Phys. B161(1979)493; Phys. Rev., D16(1977)1791;
Gunion,J.F., and Haber,H.E., Nucl. Phys. B272(1986)1; Phys. Rev., D16(1977) 1791

[5] Gunion,J.F., Haber,H.E., Paige,F.F., Tung,W.-K., and Willenbrock,S.S.D., U.C. Davis preprint, UCD-86-15 (1986)

[6] Athanathiu,G.G., Franzini,P.J. and Gilman,F.J., Phys. Rev. D32(1985)3010

[7] Bengtsson,H. and Sjostrand,T., Lund preprint, LU TP 87-3/UCLA-87-001(1987)

[8] Sjostrand,T., Lund preprint, LU-TP 85-10 (1985);

[9] Barklow,T., Proc. of the second workshop on SLC physics, SLAC Report 306 (1986)

Process	# events/year	
	(1) ~ (4)	(1) ~ (5)
$pp \rightarrow H^- t$ + spectator $\quad \hookrightarrow \tau^- + \overline{\nu}_\tau$	13	1.7
$pp \rightarrow W^*$ + spectator $\quad \hookrightarrow l^- + \overline{\nu}_l$	7.5×10^4	< 190
$pp \rightarrow W + Z$ + spec. $\quad Z \hookrightarrow \nu \overline{\nu}$ $\quad W \hookrightarrow l^- + \overline{\nu}_l$	410	< 12
$pp \rightarrow W + q(g)$ + spec. $\quad \hookrightarrow l^- + \overline{\nu}_l$	7.0×10^5	8.8×10^3

Table. Expected number of events for signal and backgrounds per year ($\tan^2(\beta) = 2.5$)

FIGURE CAPTIONS

Fig.1. Feynman diagrams for charged Higgs boson production associated with a top quark in pp collisions.

Fig.2. Feynman diagram for charged Higgs boson production via $t\bar{b}$-fusion process assuming the top distribution function in the protons. This approximation is not enough accurate to calculate reliable charged Higgs production cross section.

Fig.3. The p_T distribution of the observed "τ" candidate. The distributions are plotted after all the cuts except for the stiff lepton cut (cut (5)), and are normalized to the same number of events for the signal and the various background processes. They are not normalized to the luminosity.

Fig.4. The distribution of the variable ρ $(= \sqrt{2 \cdot p_\ell(1 - \cos\theta_{\ell,j})})$ for the signal and the various background processes are shown. They are not normalized to the luminosity. For the leptons from background processes, the distribution is peaked in the small ρ region, since they come mainly from c- or b-decays, except for the process of $W + t$ where the leptons from the top decay.

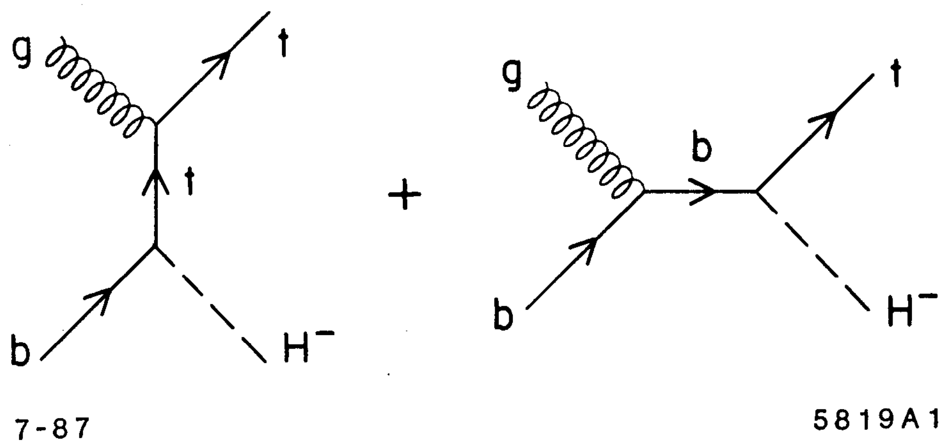


Fig. 1

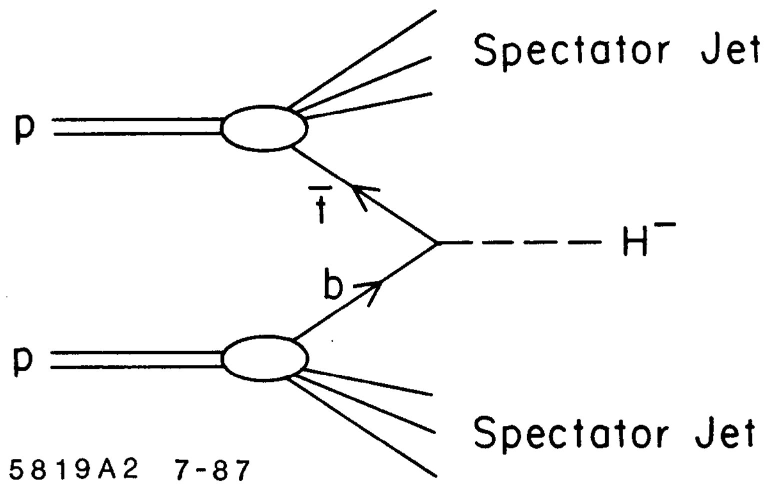
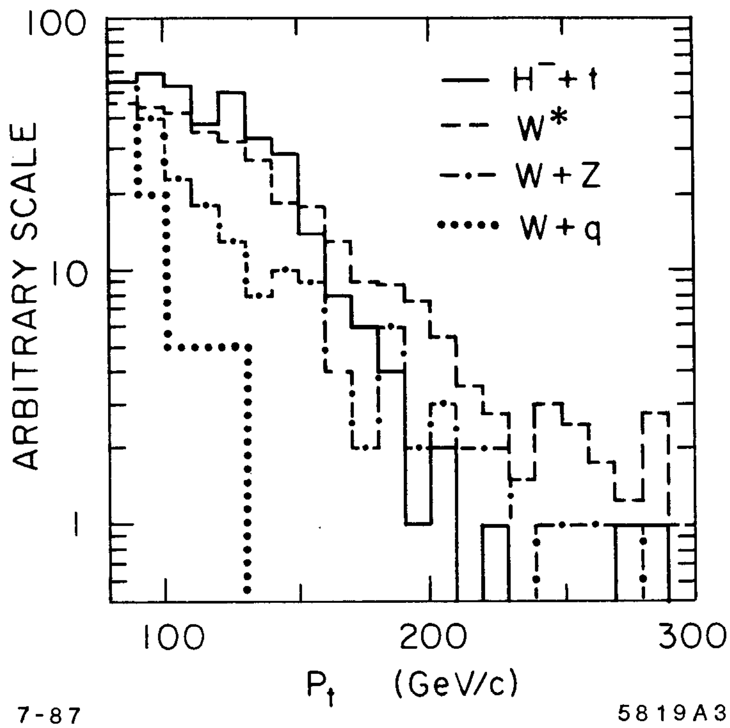
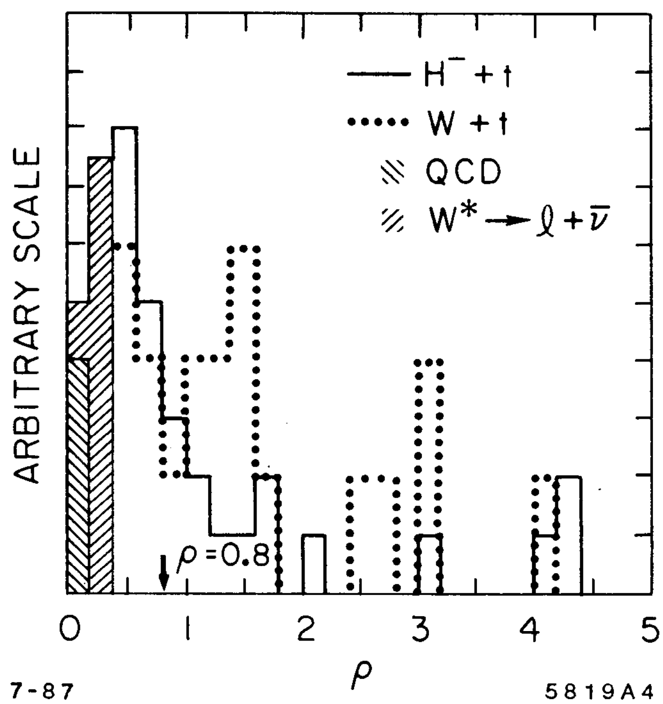


Fig. 2



100
10
1
ARBITRARY SCALE
100
200
300
P_t (GeV/c)
$H^- + t$
W*
W + Z
W + q
7-87
5819A3

Fig. 3



H⁻ + t
W + t
QCD
$W^* \rightarrow \ell + \bar{\nu}$
ARBITRARY SCALE
ρ = 0.8
0
1
2
3
4
5
ρ
7-87
5819A4

Fig. 4