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Version 2.1

Search for New Particles $X \to b\bar{b}$ Produced in Association with $W^{\pm}$ Bosons at $\sqrt{s} = 1.96$ TeV

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Abstract

We present a search for new particles decaying into $b\bar{b}$ and produced in association with $W^{\pm}$ bosons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The search uses approximately 161.6 pb^{-1} for CEM and CMUP and 149.8 pb^{-1} for CMX of the dataset accumulated by the CDF collaboration at Fermilab Tevatron. Events with an electron or muon, missing E_T and two jets, one of them b-tagged, are selected. The number of tagged events and the dijet mass distribution are consistent with the Standard Model expectations and we set a 95% confidence level upper limit on the production cross section times branching ratio as a function of the new particle mass.

0 Changes for this version

There are major additions to this note since Version 1.1. In particular, we have applied new methods of uncertainty estimations for the parton distribution function and the initial and final state radiations. We have also applied a new b-tag scale factor and new heavy flavor fractions.

1 Introduction

This note summarizes a search for new particles decaying into $b\bar{b}$ and produced in the $W^{\pm}+$ jets sample using the SECVTX b-tagger. The search signature considered here is $W^{\pm}X$ with $W^{\pm} \to e\nu$ or $\mu\nu$, and $X \to b\bar{b}$, giving final states with one high p_T lepton, large missing E_T ($\not\!\!E_T$) and two b jets. In this note we assume X is the Standard Model Higgs boson. We focus our attention on the $W^{\pm} + 2$ jets signature since it contains most of the signal, while b-tagged $W^{\pm}+ \geq 3$ jets events are dominated by $t\bar{t}$ decays. Figure 1 and 2 show the production cross section of the Standard Model Higgs boson in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and the Higgs boson branching ratio as a function of the Higgs boson mass.

This note is organized as follows: Section 2 and 3 introduce the dataset and event selection. In Section 4 we try to optimize the jet E_T selection criteria. Section 5 presents the estimated number of events. Finally, Section 6, 7 and 8 summarize the results, cross checks and conclusion.

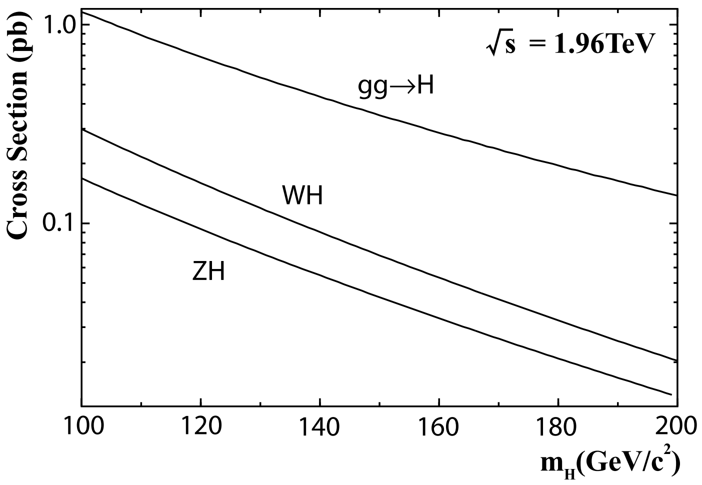


Figure 1: The $W^{\pm}H$ production cross section as a function of the Higgs boson mass (m_H) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

2 Data and MC samples

The data used in this analysis are from runs in the silicon good run list version 4 defined by the DQM group. In particular, good runs with numbers in the range 141544-167715 [1] represent an integrated luminosity of 161.6 ± 9.5 pb^{-1}. (The offline luminosity has been corrected by a factor of 1.019 [1] and assigned a 6% uncertainty [2].) The CMX muon dataset is limited to runs after 150145, a total of 149.8 ± 8.8 pb^{-1}. We use the official TopNtuples produced with offline version 4.11.1. Silicon tracks in these ntuples have been refit using the updated alignment and refitter available in 4.11.1.

We use the standard Monte Carlo samples provided by the top group for the background studies, see the details at the top web page for official MC samples. For the signal acceptance and systematic studies, we have generated many $W^{\pm}H$ samples with PYTHIA and different Higgs boson masses using the standard Monte Carlo procedures outlined in 4.9.1.

3 Event Selection

The event selection starts with the standard $W^{\pm}$+ jets sample of the top analysis [3]. The baseline cuts for a good lepton are summarized in Table 1, 2 and 3. We require events to pass the ELECTRON_CENTRAL_18 trigger for CEM electrons, the MUON_CMUP18 trigger for CMUP muons, and the MUON_CMX18 trigger for CMX muons. The expanded acceptance of the top dilepton cross section analysis necessitates an expanded veto for the lepton + jets analysis. We veto the events where the sum of the tight central leptons and plug electrons are greater than 1. We use jet energies that have been corrected using level 4 jet energy corrections defined in Ref. [4]. The $W^{\pm}$ events are selected by requiring that $\not\!\!E_T > 20$ GeV, where $\not\!\!E_T$ is corrected for the tight muon and all level 4 corrected jets in $|\eta| < 2.5$ and $E_T > 8$ GeV.

In addition to the $W^{\pm}$ boson event selections, events which are flagged as Z^0 bosons and cosmic rays are removed. In order to further reduce the top contributions, we remove events with a high p_T isolated track ($p_T^{seed} > 20$ GeV/c) and charge opposite to the primary lepton. The track isolation is

[1] We remove run 164844 (CLC error), 163463 and 163474 (wrong beamline) from the good runs.

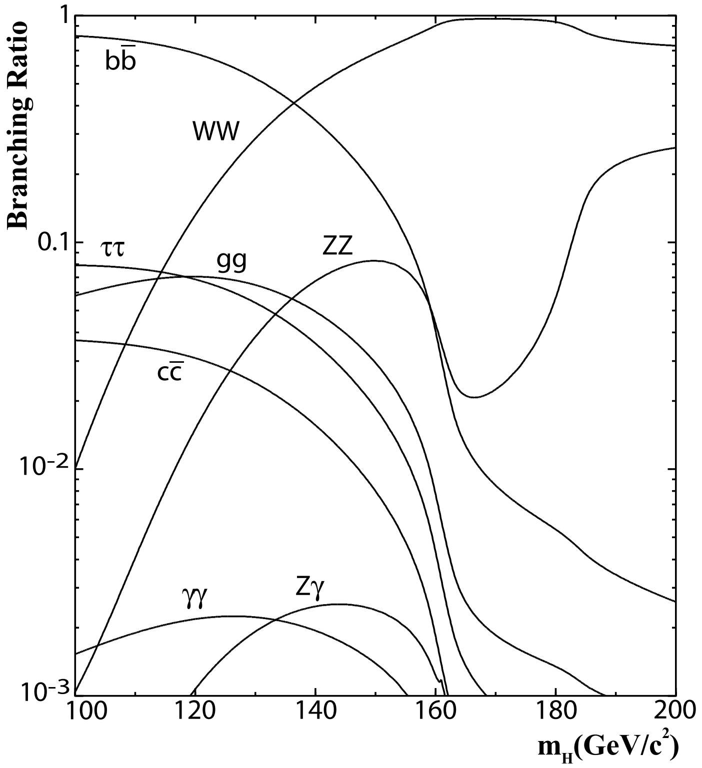


Figure 2: The Higgs boson branching ratio as a function of the Higgs boson mass (m_H).

defined as $p_T^{seed}/(p_T^{seed} + \Sigma p_T) > 0.9$ where p_T^{seed} is the seed track p_T and Σp_T is the sum of track p_T (> 0.5 GeV) in a cone of radius 0.4 around the seed track. We also require that there are no any extra jets with $E_T^{raw} > 8$ GeV in the forward region ($2.0 <| \eta |< 3.0$) or two more extra jets with $E_T^{raw} > 8$ GeV and $E_T < 15$ GeV in the central region ($| \eta |< 2.0$), where E_T^{raw} is uncorrected jet E_T.

To classify the remaining events according to jet multiplicity, we select the jets with $E_T > 15$ GeV and $| \eta |< 2.0$. In the next section, we try to optimize the jet E_T selection criteria. The $W^\pm + 2$ jets bin is expected to contain most of the signal, while the other bins are used to check the background calculation. In order to enhance the signal in the $W^\pm + 2$ jets bin, we require that one or both of the jets be b-tagged by the SECVTX algorithm. Figure 3 shows an event display for the double tagged event in the $W^\pm + 2$ jets sample.

4 Cut Optimization

We optimize the 1st and 2nd leading jet E_T selection criteria by varying the cuts. Table 4 shows the 1st and 2nd leading jet E_T selection criteria.

We evaluate a significance for each set of cuts. The significance is defined as $S/\sqrt{B}$, where S is the number of signals and B is the number of backgrounds in a mass window, which is within $\pm 1.5\sigma$ of the Higgs boson mass. Figure 4 shows the significance as a function of the jet E_T selection criteria. Since the significance is not sensitive to the 1st leading jet E_T, we require the 1st leading jet $E_T > 15$ GeV and the 2nd leading jet $E_T > 15$ GeV, to be the same ones used in the lepton + jets group.

Central Electron Variable	Value
Fiducial and CEM	$= 1$
E_T	≥ 20 GeV
p_T	≥ 10 GeV/c
E/p (if $p_T \leq 100$ GeV/c)	≤ 2.0
E_{HAD}/E_{EM}	$\leq 0.055 + 0.00045 \times E$
L_{shr}	≤ 0.2
$\mid \Delta z \mid$	≤ 3 cm
$Q \times \Delta x$	≥ -1.5 and ≤ 3.0 cm
χ^2_{strip}	≤ 10
$\mid \Delta z_0 \mid$	≤ 60 cm
$\mid z_0^{vtx} - z_0^{electron} \mid$	≤ 5 cm
Good COT Axial Segments	≥ 3
Good COT Stereo Segments	≥ 3
Isolation	≤ 0.1
Not a conversion	$\Lambda > 0.04$ or $\Delta r > 0.2$

Table 1: CEM electron selection criteria [3].

Plug Electron Variable	Value
E_T	≥ 20 GeV
E_{HAD}/E_{EM}	≤ 0.05 (if $E_T \leq 100$ GeV)
	$\leq 0.05 + 0.026 \times \log(E_{EM}/100.0)$ (if $E_T > 100$ GeV)
Towers in χ^2 fit	≥ 1
PEM 3×3 χ^2	≤ 10.0
PES U cluster 5×9 ratio	> 0.65 (if $E_T < 100$ GeV)
PES V cluster 5×9 ratio	> 0.65 (if $E_T < 100$ GeV)
PES η	$> 1.2, < 2.5$
Number PES clusters	≥ 1
ΔR PEM-PES	≤ 3 cm
Phoenix match	Yes
Track $\mid z_0 \mid$	≤ 60 cm
Number PHX Si hits	≥ 3
Isolation	≤ 0.1

Table 2: PEM electron selection criteria [3].

Central Muon Variable	Value
Region	CMUP or CMX
p_T	$\geq$ 20 GeV/c
E_{EM}	$\leq \max(2, 2 + 0.0115 \times (p - 100))$
E_{HAD}	$\leq \max(6, 6 + 0.0280 \times (p - 100))$
$\mid \Delta x \mid_{CMU}$	$\leq$ 3.0 cm
$\mid \Delta x \mid_{CMP}$	$\leq$ 5.0 cm
$\mid \Delta x \mid_{CMX}$	$\leq$ 6.0 cm
$\mid z_0 \mid$	$\leq$ 60 cm
$\mid z_0^{vtx} - z_0^{muon} \mid$	$\leq$ 5 cm
$\mid d_0 \mid$ if no Si hits	$\leq$ 0.2 cm
$\mid d_0 \mid$ if Si hits	$\leq$ 0.02 cm
Good COT Axial Segments	$\geq$ 3
Good COT Stereo Segments	$\geq$ 3
Isolation	$\leq$ 0.1
COT exit radius (CMX-only)	$\geq$ 140 cm

Table 3: CMUP and CMX muon selection criteria [3].

	2nd Leading E_T^{jet} (GeV)							
1st Leading E_T^{jet} (GeV)	15	20	25	30	35	40	45	50
15	$\surd$							
20	$\surd$	$\surd$						
25	$\surd$	$\surd$	$\surd$					
30	$\surd$	$\surd$	$\surd$	$\surd$				
35	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$			
40	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		
45	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	
50	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$

Table 4: The 1st and 2nd leading jet E_T selection criteria.

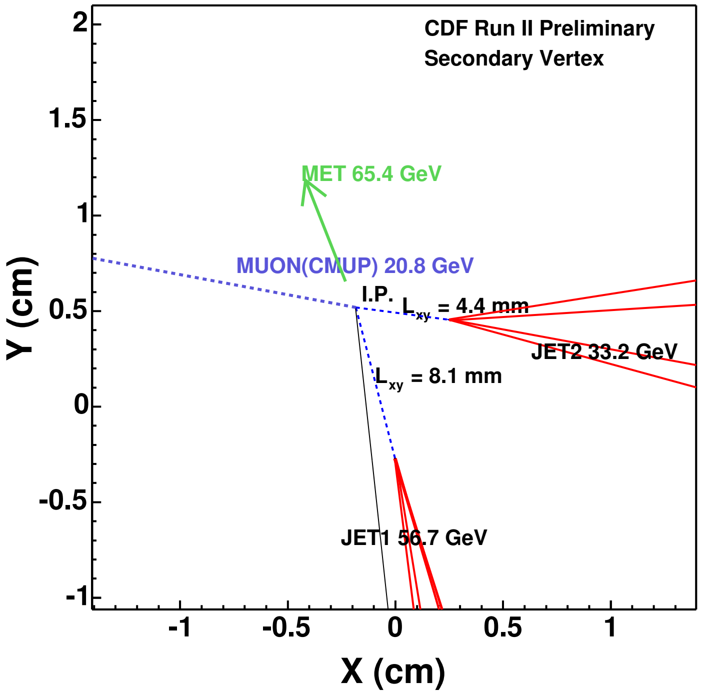


Figure 3: The event display for the double tagged event (run 166063, event 279746) in the $W^{\pm} + 2$ jets sample.

5 Event Estimation

The following backgrounds must be accounted for in the tagged $W^{\pm}$ + jets sample:

- Mistags or false tags due to vertex and track resolution,
- $W^{\pm} + b\bar{b}$, $W^{\pm} + c\bar{c}$ and $W^{\pm} + c$,
- Non-$W^{\pm}$ (QCD),
- $t\bar{t}$, single top, $W^{+}W^{-}$, $W^{\pm}Z^{0}$, $Z^{0}Z^{0}$ and $Z^{0} \to \tau^{+}\tau^{-}$.

The rate of mistags, or falsely tagged jets, is derived from a generic jet sample in varying bins of ϕ, η, jet E_T, track multiplicity with a jet and event sum E_T [5]. Tag rate probabilities are summed for all taggable jets in the event. Since the double mistag rate is small [6], this sum is a good approximation of the event tag rate. Negative mistags, tags with unphysical negative decay lengths, are calculated as an estimate of falsely tagged jets, independent of the first order of heavy flavor content in the generic jet sample. Errors on the mistag estimates include statistical errors from the matrix itself and an additional 8% error from systematic uncertainties. A recent study [7] indicates that the positive mistag rate is enhanced by light-flavor secondary vertices and material interactions in the silicon detectors. As a result, the mistag rate in the positive side is estimated by multiplying the negative mistag rate by a factor of 1.2 ± 0.1.

Because it is used to normalize many background estimations, the number of events in the signal region before tagging (lepton isolation < 0.1 and $\not\!\!E_T > 20$ GeV) is listed in Table 5 as a function of jet multiplicity.

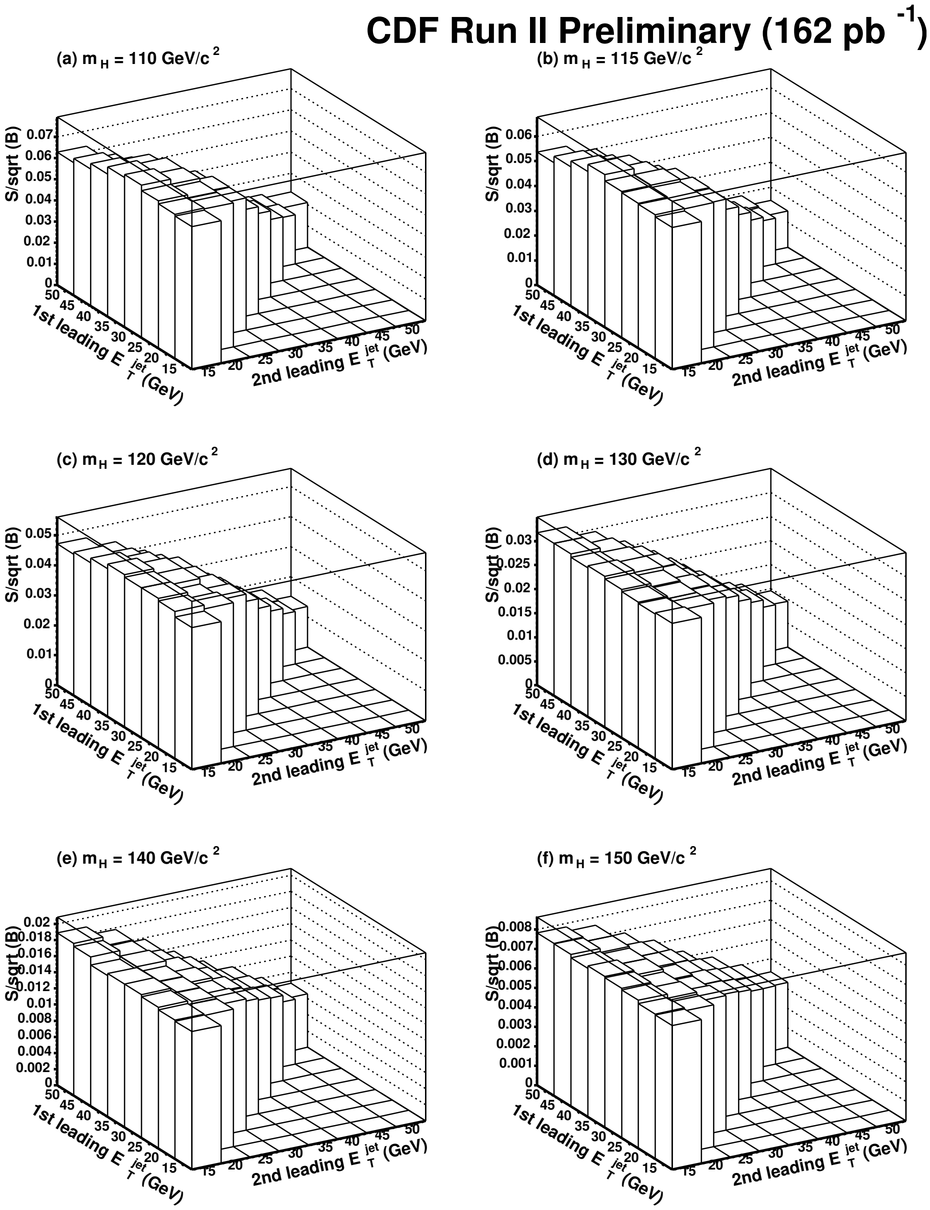


Figure 4: The significance as a function of 1st and 2nd leading jet E_T selection criteria. The significance is not sensitive to the 1st leading jet E_T. (a)m_H = 110 GeV/c^2, (b)m_H = 115 GeV/c^2, (c)m_H = 120 GeV/c^2, (d)m_H = 130 GeV/c^2, (e)m_H = 140 GeV/c^2, (f)m_H = 150 GeV/c^2.

Jet multiplicity	1 jet	2 jets	3 jets	≥ 4 jets
CEM electrons	7707	1228	197	55
CMUP muons	3740	582	78	22
CMX muons	1961	262	39	5
Total	13408	2072	314	82

Table 5: The number of events in the signal region before tagging as a function of jet multiplicity.

Jet multiplicity	1 jet	2 jets	3 jets	≥ 4 jets
Mistags	36.15 ± 7.06	14.06 ± 2.58	3.98 ± 0.86	2.05 ± 0.45
$W^{\pm} + b\bar{b}$	32.19 ± 10.17	19.10 ± 5.87	3.67 ± 1.08	0.66 ± 0.20
$W^{\pm} + c\bar{c}$	11.92 ± 3.53	6.83 ± 2.18	1.20 ± 0.41	0.23 ± 0.09
$W^{\pm} + c$	29.96 ± 8.04	6.54 ± 1.81	1.03 ± 0.31	0.12 ± 0.05

Table 6: The estimated mistags and $W^{\pm}$ + heavy flavor background contributions.

We refer the reader to sections 4, 5, 6 and 7 of the dedicated note [8] for a detailed discussion of the backgrounds.

5.1 Mistags and $W^{\pm}$ + Heavy Flavor Backgrounds

We use the standard method 2 background calculation [8, 9] including our analysis requirements. The results are shown in Table 6.

5.2 Non-$W^{\pm}$ (QCD) Background

We scale the Non-$W^{\pm}$ numbers from Ref. [10] using the number of taggable jets. Table 7 shows estimated Non-$W^{\pm}$ contributions.

5.3 MC Derived Backgrounds

The normalization of the diboson, single top and $Z^0 \to \tau^+\tau^-$ backgrounds is based on the theoretical cross sections [11, 12, 13, 14], the measured luminosity, the acceptance and the b-tagging efficiency. The cross sections are listed in Table 8. We normalize to an integrated luminosity of 161.6 pb^{-1} for CEM and CMUP and 149.8 pb^{-1} for CMX.

The MC acceptance is corrected for lepton ID's, trigger efficiencies, and z vertex cut, as done for the $t\bar{t}$ acceptance [3]. The tagging efficiency is scaled by the MC/data scale factor of 0.82 ± 0.06 for b's. We double the uncertainty for the tagging charm jets such as in $W^{\pm} \to c\bar{s}$ [8].

Jet multiplicity	1 jet	2 jets	3 jets	≥ 4 jets
$N^{tag}_{Non-W^{\pm}}$ electrons	16.70 ± 1.92	7.33 ± 1.14	2.24 ± 0.45	0.93 ± 0.20
$N^{tag}_{Non-W^{\pm}}$ muons	3.64 ± 0.56	1.14 ± 0.28	0.56 ± 0.16	0.23 ± 0.08

Table 7: The estimated Non-$W^{\pm}$ background contributions.

Process	Cross Section (pb)
W^+W^-	13.25 ± 0.25
$W^\pm Z^0$	3.96 ± 0.06
Z^0Z^0	1.58 ± 0.02
$t\bar{t}$	6.7 ± 0.9
single top (s-channel)	0.88 ± 0.05
single top (t-channel)	1.98 ± 0.08
$Z^0 \to \tau^+\tau^-$	238.5 ± 0.6

Table 8: The theoretical cross sections to estimate the MC derived background contributions.

Jet multiplicity	1 jet	2 jets	3 jets	$\geq$ 4 jets
W^+W^-	0.45 ± 0.07	0.95 ± 0.14	0.25 ± 0.05	0.05 ± 0.02
W^+Z^0	0.35 ± 0.07	0.94 ± 0.14	0.23 ± 0.05	0.05 ± 0.02
Z^0Z^0	0.02 ± 0.01	0.06 ± 0.02	0.02 ± 0.01	0.00 ± 0.00
$Z^0 \to \tau^+\tau^-$	0.90 ± 0.45	0.54 ± 0.33	0.00 ± 0.00	0.00 ± 0.00

Table 9: The expected diboson and $Z^0 \to \tau^+\tau^-$ background contributions.

The diboson background consists of W^+W^-, $W^\pm Z^0$ and Z^0Z^0 production. One of the bosons decay into leptons and the other boson decay into jets with charm or bottom quarks. The Z^0Z^0 background contribution is completely negligible, but is included for completeness. The diboson background prediction is shown in Table 9.

The $t\bar{t}$ and single top backgrounds are shown in Table 10. The single top production at Tevatron comes from both the s-channel and t-channel processes. We use separate MC samples for each process to model the acceptance and tagging efficiencies.

As the other background, we consider a background from $Z^0 \to \tau^+\tau^-$. In this case, one of the τ decays leptonically and the other τ decays to 3 or more charged tracks. The 3-prong τ decay could be identified as a jet with a displaced vertex due to the τ lifetime. The estimated background is given in Table 9.

5.4 Summary of Event Estimation

Figure 5 and Table 11 summarize the number of observed tagged events along with the estimated background events. The expectations are in reasonably good agreement with the $W^\pm +$ jets data.

Jet multiplicity	1 jet	2 jets	3 jets	$\geq$ 4 jets
$t\bar{t}$	0.43 ± 0.10	5.15 ± 0.96	12.84 ± 2.36	20.32 ± 3.72
single top (s-channel)	0.36 ± 0.05	1.73 ± 0.23	0.47 ± 0.06	0.11 ± 0.02
single top (t-channel)	0.79 ± 0.10	2.08 ± 0.26	0.43 ± 0.06	0.06 ± 0.01

Table 10: The expected top and single top background contributions.

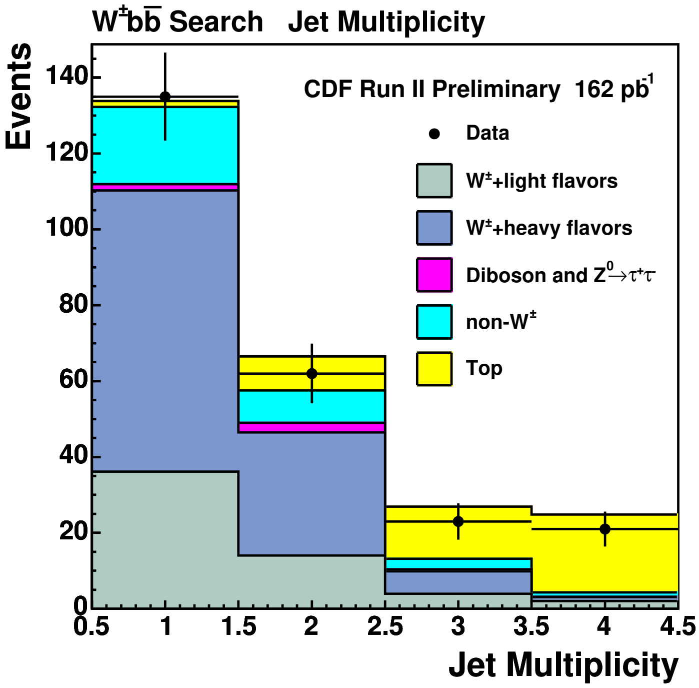


Figure 5: The number of observed positive tagged events and the background summary as a function of jet multiplicity. The integrated luminosities are 161.6 pb^{-1} for CEM and CMUP and 149.8 pb^{-1} for CMX.

6 Upper Limit

6.1 Acceptance

The acceptance for identifying $W^{\pm}H \rightarrow \ell\nu b\bar{b}$ events is calculated from a combination of data and PYTHIA Monte Carlo samples of $p\bar{p} \rightarrow W^{\pm}H \rightarrow W^{\pm}b\bar{b}$ events as a function of the Higgs boson mass (m_H) using the cuts described above. The scale factors for lepton identification (ID) efficiencies are 0.965 ± 0.006 [15], 0.939 ± 0.007 and 1.014 ± 0.007 [16] for CEM, CMUP and CMX, respectively. The scale factors for muon reconstruction efficiencies are 0.945 ± 0.06 and 0.992 ± 0.003 [16] for CMUP and CMX, respectively. The trigger efficiencies are 0.9656 ± 0.0006, 0.887 ± 0.007 and 0.954 ± 0.006 [15, 16] for CEM, CMUP and CMX, respectively. The scale factor of SECVTX b-tagging efficiency is 0.82 ± 0.06 (stat.+sys.) [8, 17]. Although the scale factor for c-tagging efficiency has not been measured, we have no reason to expect it to be very different from the scale factor for b-tagging. We take 0.82 ± 0.12 (stat.+sys.) for c-tagging, with an increased systematic error to account for extra uncertainty. The total acceptance is calculated as a production of the kinematic and geometric acceptance, the lepton ID efficiency, the trigger efficiency and the b-tagging efficiency. A 11% systematic uncertainty comes from uncertainties in the modeling of initial (3%) and final (6%) state radiations, the parton distribution function (2%), the jet energy scale (3%), the b-tag efficiency (6%), jet energy smearing [2] [18] (1%), the soft jet modeling (1%), the electron and muon trigger efficiencies ($0.06\%, 0.79\%, 0.63\%$ for CEM, CMUP and CMX,respectively), the electron and muon ID efficiencies (5%). The acceptance increases linearly from $1.5 \pm 0.2\%$ to $1.8 \pm 0.2\%$ as m_H increases from 110 to 150 GeV$/c^2$, shown in Figure 6.

[2] The difference of jet energy resolution between the data and MC.

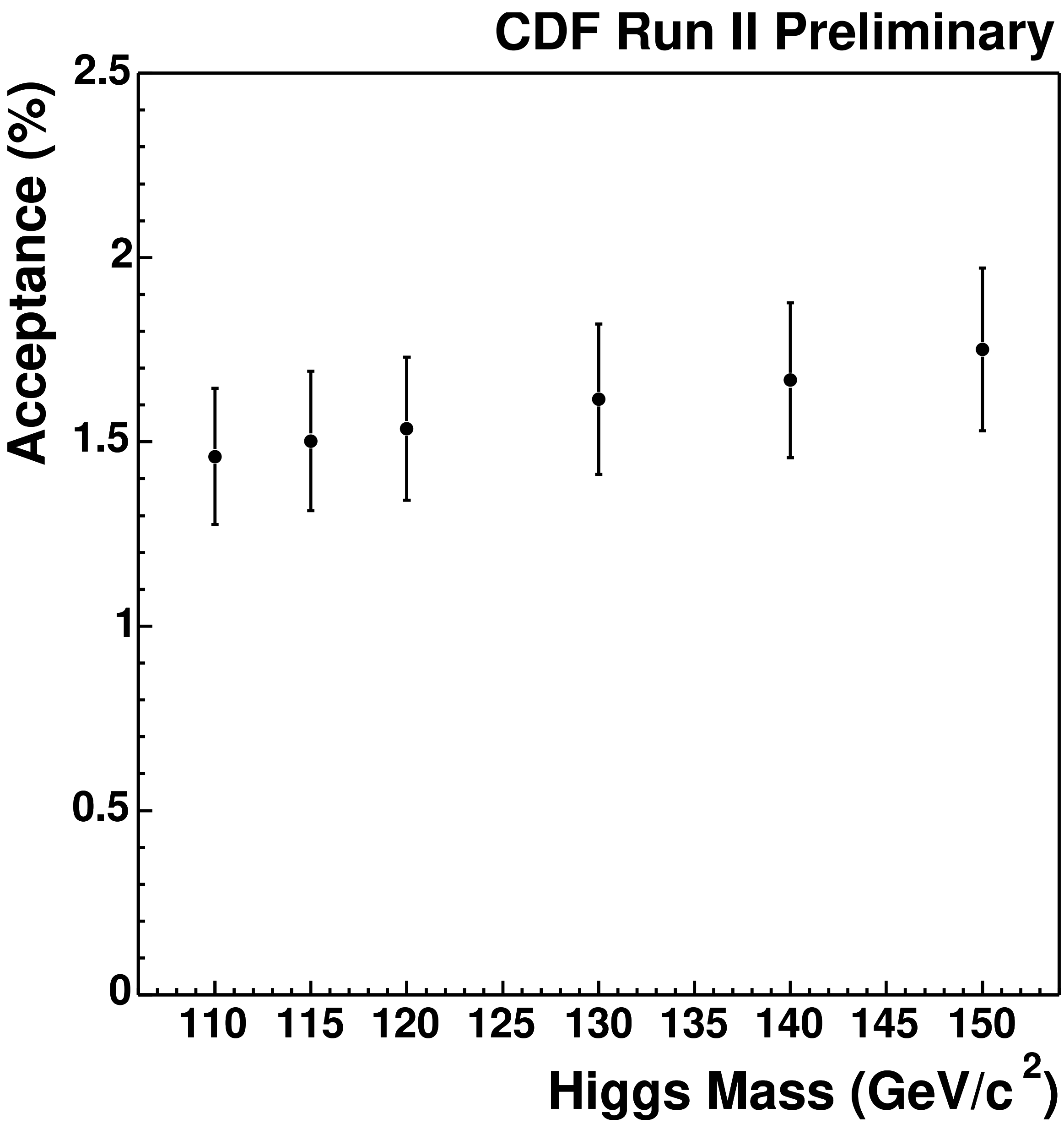


Figure 6: The total $W^{\pm}H \to \ell\nu b\bar{b}$ acceptance as a function of the Higgs boson mass.

Background	$W^{\pm}$ + 1 jet	$W^{\pm}$ + 2 jets	$W^{\pm}$ + 3 jets	$W^{\pm}$ + $\geq$ 4 jets
Events before tagging	13417	2072	313	82
mistags	36.2 ± 7.1	14.1 ± 2.6	4.0 ± 0.9	2.0 ± 0.5
$W^{\pm} + b\bar{b}$	32.2 ± 10.2	19.1 ± 5.8	3.7 ± 1.1	0.7 ± 0.2
$W^{\pm} + c\bar{c}$	11.9 ± 3.5	6.8 ± 2.2	1.2 ± 0.4	0.2 ± 0.1
$W^{\pm} + c$	30.0 ± 8.0	6.5 ± 1.8	1.0 ± 0.3	0.1 ± 0.0
Diboson/$Z^0 \to \tau^+\tau-$	1.7 ± 0.6	2.5 ± 0.6	0.5 ± 0.1	0.1 ± 0.0
QCD	20.3 ± 2.0	8.5 ± 1.2	2.8 ± 0.5	1.1 ± 0.2
$t\bar{t}$	0.4 ± 0.1	5.1 ± 1.0	12.8 ± 2.4	20.3 ± 3.7
single top	1.2 ± 0.2	3.8 ± 0.5	0.9 ± 0.1	0.2 ± 0.0
Total Background	133.9 ± 17.5	66.5 ± 9.0	26.9 ± 3.2	24.8 ± 3.8
Observed positive tags	135	62	23	21

Table 11: The number of observed positive tagged events and the background summary for an integrated luminosity of 161.6 pb^{-1} for CEM and CMUP and 149.8 pb^{-1} for CMX.

6.2 95% C.L. upper limit

We perform a direct search for a resonant mass peak in the reconstructed dijet invariant mass distribution with the level 7 jet energy correction. Figure 7 shows the dijet mass distribution. Since there is no mass peaks as expected from the Higgs boson, we set an upper limit on the production cross section times branching ratio of $p\bar{p} \to W^{\pm}H$ as a function of m_H by using the number of events in the $W^{\pm}$ + 2 jets sample. We assume the dijet mass distribution in the data consists of QCD (mistags, $W^{\pm} + b\bar{b}$, $W^{\pm} + c\bar{c}$, $W^{\pm} + c$ and diboson), TOP ($t\bar{t}$ and single top) and $W^{\pm}H$ events. A binned maximum likelihood technique is used to estimate the number of $W^{\pm}H$ signal events by constraining the number of QCD and TOP events to the expectation within the statistical and systematic uncertainties. The expected number of events (μ) in each mass bin is

$$\mu = f_{QCD} \cdot N_{QCD} + f_{TOP} \cdot N_{TOP} + f_{W^{\pm}H} \cdot (\varepsilon \cdot \mathcal{L} \cdot \sigma_{W^{\pm}H} \cdot \mathrm{Br}\ (H \to b\bar{b})),$$

where f_{QCD}, f_{TOP} and $f_{W^{\pm}H}$ are the expected fraction of events in a given mass bin predicted by Monte Carlo and N_{QCD}, N_{TOP}, ε, $\mathcal{L}$ and $\sigma_{W^{\pm}H}$ are the expected number of QCD and TOP events, the detection efficiency, the luminosity and the unknown $W^{\pm}H$ cross section, respectively.

The corresponding likelihood is

$$L = \prod_{i=bin} \frac{\mu_i^{N_i} \cdot e^{-\mu_i}}{N_i!},$$

where N_i is the observed events from $W^{\pm}+2$ jets sample. Figure 8 shows the 95% C.L. upper limit as a function of m_H. In Figure 8 the cross section of the Technicolor process ($p\bar{p} \to W^{\pm}\pi_T^0$) is also put as the comparison. Figure 9 shows the pseudo experiment results. The measurement is consistent with the pseudo experiment results. Although we have a much improved limit over the Run 1 [19], the sensitivity of the present search is limited by statistics to a cross section approximately one order of magnitude higher than the predicted cross section for the Standard Model Higgs boson production.

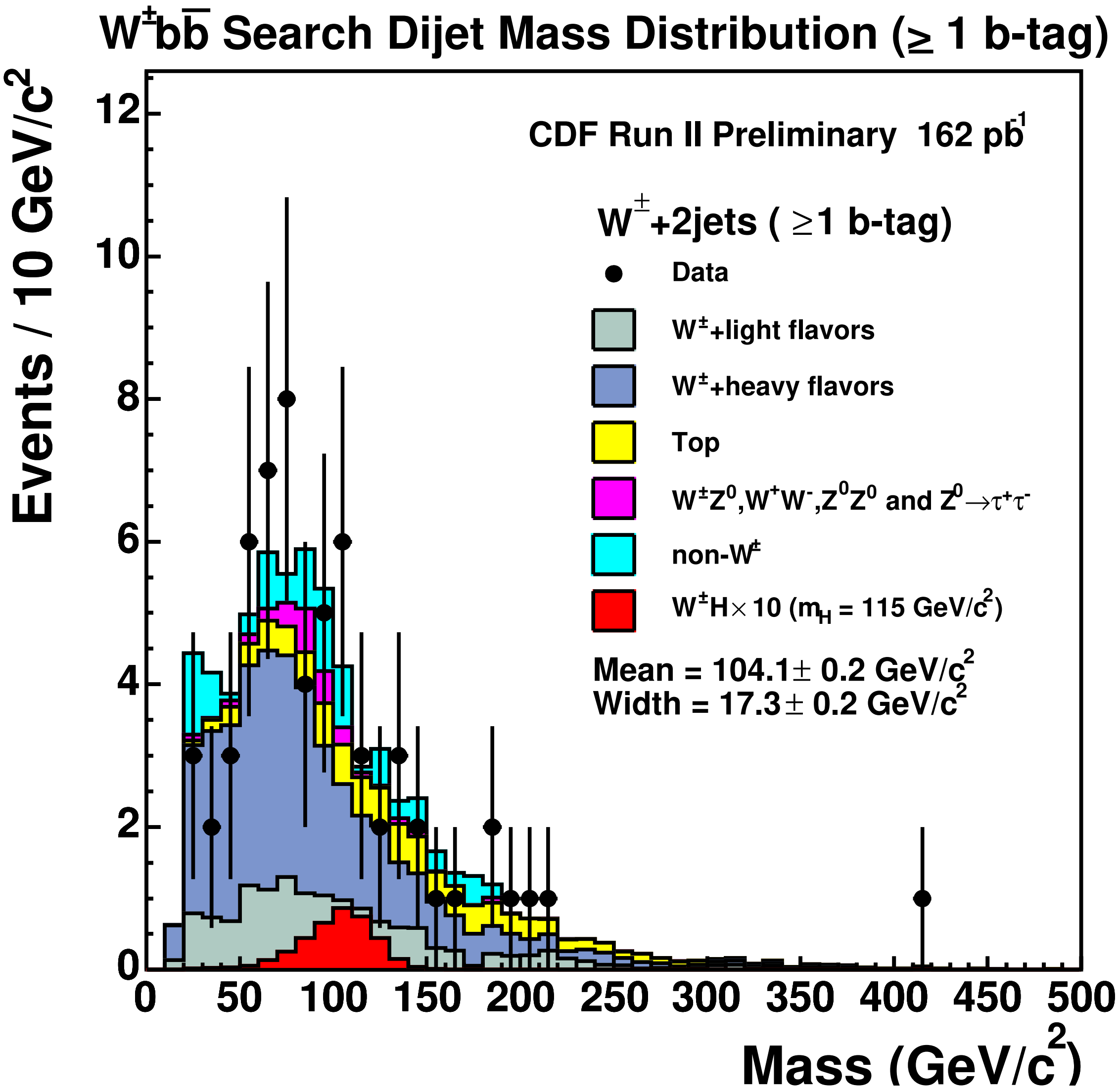


Figure 7: The dijet mass distribution in the data along with the background expectations and the scaled Higgs boson mass distributions by a factor of 10. The Higgs boson mass is assumed to be 115 GeV$/c^2$.

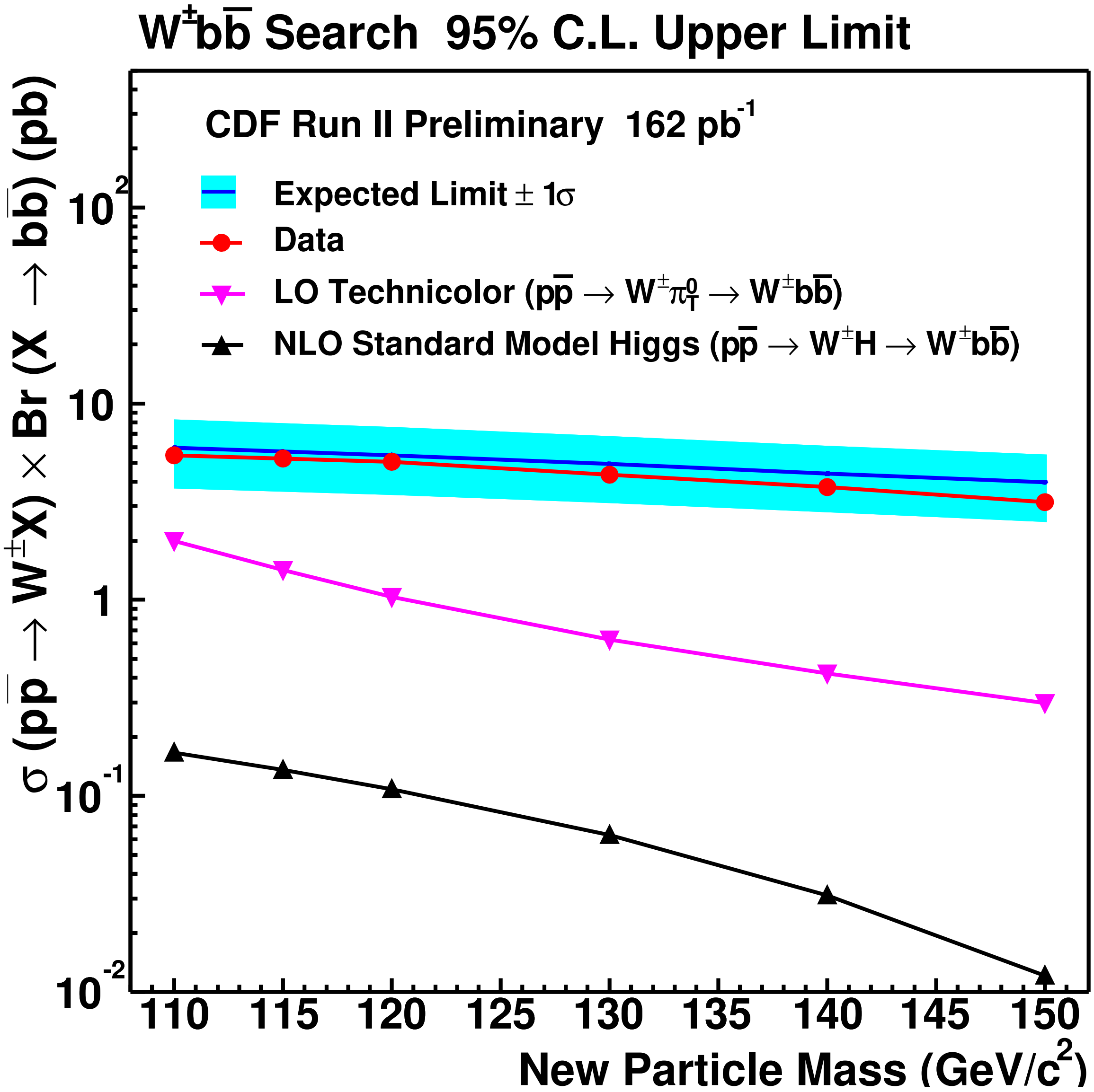


Figure 8: The 95% C.L. upper limit (red circle) on the $W^{\pm}H$ cross section as a function of the Higgs boson mass. Also shown is the theoretical cross section (black triangle) for the production of a Standard Model Higgs boson in association with a $W^{\pm}$ boson, and the pseudo experiment results (blue square). As for the comparison, the production cross section of the Technicolor process ($p\bar{p} \to W^{\pm}\pi^0_T$) is also included (empty black triangle).

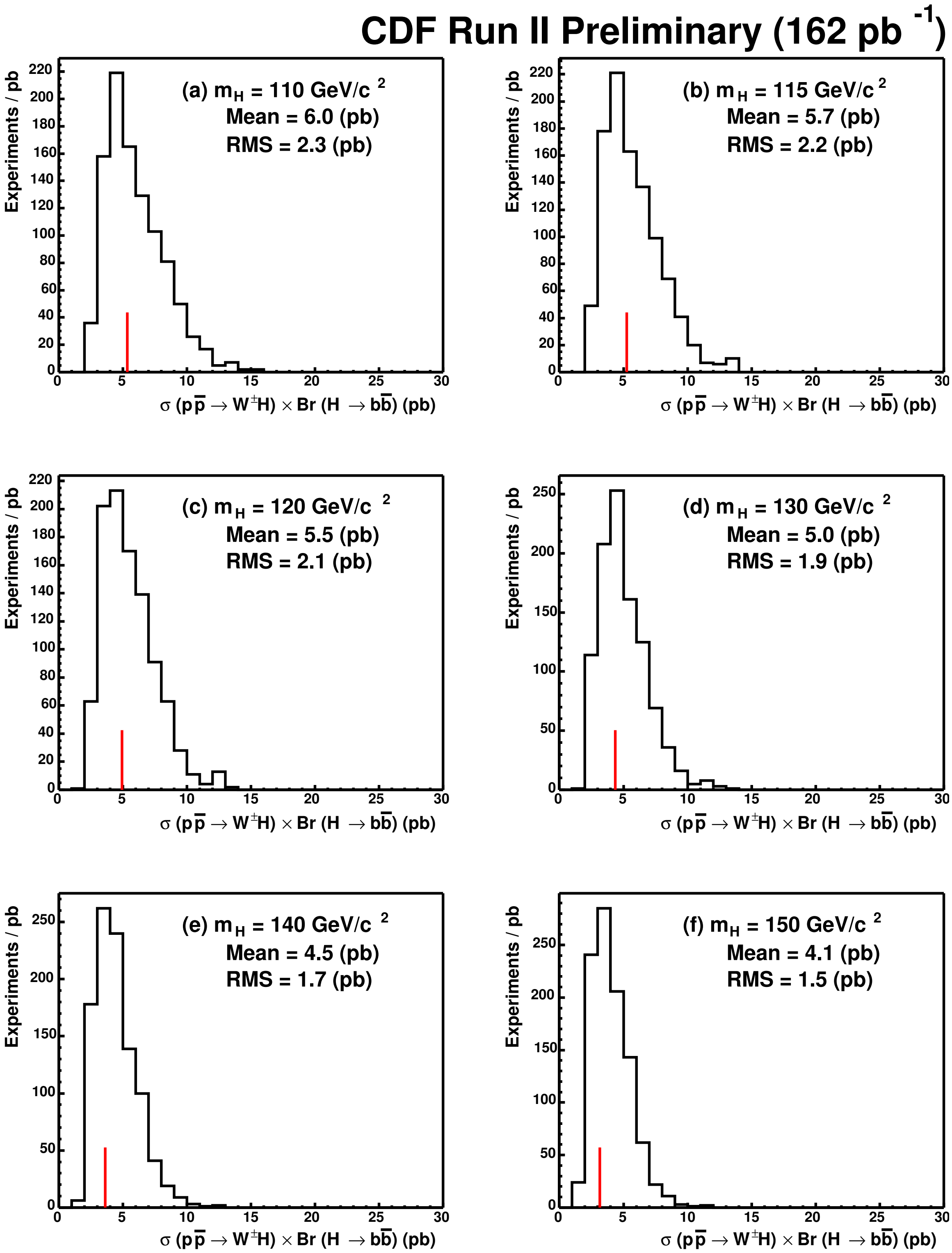


Figure 9: The pseudo experiment results. The red line shows the results from data. (a)$m_H = 110$ GeV$/c^2$, (b)$m_H = 115$ GeV$/c^2$, (c)$m_H = 120$ GeV$/c^2$, (d)$m_H = 130$ GeV$/c^2$, (e)$m_H = 140$ GeV$/c^2$, (f)$m_H = 150$ GeV$/c^2$.

7 Cross Checks and Future Improvements

7.1 Pretag Dijet Mass Distributions

As a cross check, we have compared the pretag dijet mass distribution with the expectation from the various backgrounds, which are shown in Figure 10. The agreement between the data and MC gives us some confidence towards our detector simulation and background calculations.

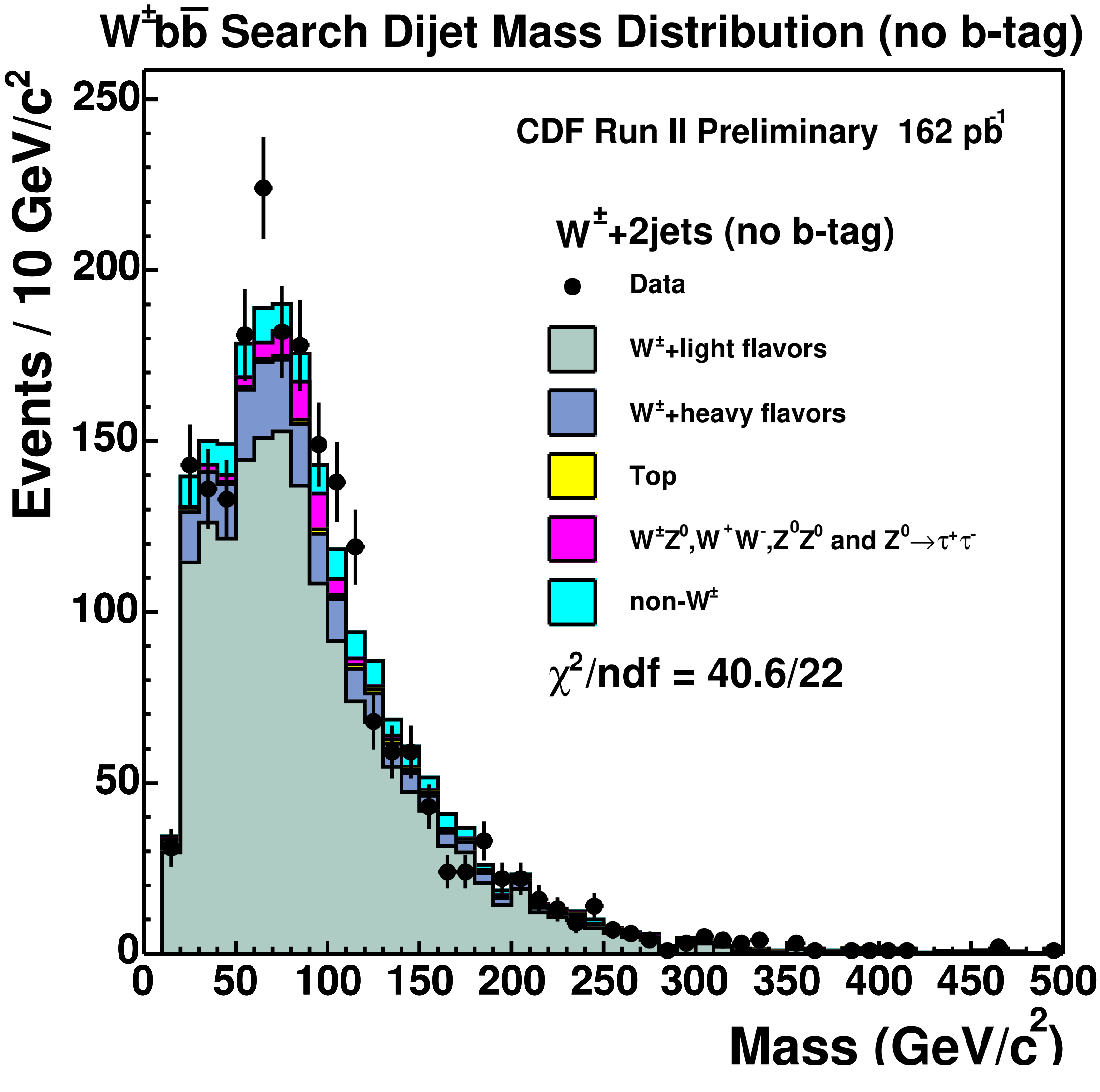


Figure 10: The dijet mass distribution before tagging.

7.2 Significance Comparison

We compared the significance with the Run 1 and the Higgs sensitivity report ones [20, 21, 22]. The results are shown in Table 12. The significance of this analysis is in line in between the Run 1 and the Run 2 Higgs sensitivity studies with current detector configuration, so called "CASE 0", without extension to higher η for either lepton identification or b-tagging.

	Run2	Run1		Run2 Higgs sensitivity report	
	This Analysis	Cut Based	NN	CASE 0	
Mass Resolution	17%	15%		15%	10%
S	0.24	0.31	0.24	0.13	0.13
B	18.2	50.7	18.3	3.2	2.1
$S/\sqrt{B}$	0.057	0.04	0.056	0.075	0.09

Table 12: The significance comparison of different analysis. The "CASE 0" in the Run2 Higgs sensitivity report uses the same lepton selection and SECVTX b-tagging as this analysis. There is no extension of higher η for either lepton identification or b-tagging. Both jets are required to be b-tagged, but allowing the second b-tag to be significantly looser (SECVTX or Jet Probability) than the first one (SECVTX).

7.3 Future Improvements

We have some plans to improve these results towards future improvements.

1. Including plug electrons,
2. Improvement of the jet energy resolution,
3. Improvement of the b-tagger and including other b-taggers (jet probability, soft lepton tag) for double tagging.,
4. Combining with other channel results ($Z^0H \to \nu\nu b\bar{b}$, ..., etc),

These will improve the sensitivity.

8 Conclusion

We performed a search for new particles decaying into $b\bar{b}$ and produced in association with a $W^{\pm}$ boson at the Run 2 dataset. The dijet mass spectrum shows no significant excess of events in the b-tagged $W^{\pm} + 2$ jet events. We set a 95% C.L. upper limit on the production cross section times branching ratios as a function of the Higgs boson mass. From Figure 8 we see that the sensitivity of the present search is limited by statistics to a cross section approximately one order of magnitude higher than the predicted cross section for the Standard Model Higgs boson production.

9 Acknowledgments

We would like to thank many people for their insights and useful discussions on this subject. Special thanks to M. Kruse for providing us his likelihood code and to S. Mrenna, J. Nielsen and T. Tomura for many useful discussions.

A Systematic Uncertainty

In this section we describe some details how to estimate the systematic uncertainties. We use the same procedures that used by the lepton + jets group for their $t\bar{t}$ acceptance studies [3]. The acceptances are estimated with the approximately 150K simulated $WH \to l\nu b\bar{b}$ events in PYTHIA

Parameter	decreasing	default	increasing
PARJ(81) for ISR	0.15	0.29	0.58
PARP(64) for FSR	0.50	1.00	2.00

Table 13: PYTHIA parameters for the initial and final state radiation.

for each Higgs mass. There are systematic uncertainties associated with the lepton identification, trigger efficiencies, b-tagging, jet-energy correction, and the Monte Carlo modeling, which includes the initial state radiation (ISR), the final state radiation (FSR), and parton density structure functions (PDF). The scale factors for lepton ID and b-tagging are determined from the data and the Monte Carlo. The lepton trigger efficiencies are directly measured from the data. We change the central value $\pm 1\sigma$ of these efficiencies to estimate their systematic uncertainties.

A.1 Initial and Final State Radiation Systematic

We have generated PYTHIA Monte Carlo samples with different PARP(64) and PARJ(81) values for increasing or decreasing amount of initial and final state radiation. Table 13 shows values used for the simulation. The percent change in acceptance are 3% systematic for ISR and 6% systematic for FSR.

A.2 Parton Distribution Function

We use the reweighting technique developed by Stephen Miller [23]. For each event in the default PYTHIA WH sample, we calculate a weight according to the relevant PDF set. The sum of the weights gives the expected change in acceptance. We take the differences in quadrature between the central value of NLO CTEQ6M and the rest of 20 CTEQ eigenvectors and find a systematic of 2%.

A.3 Jet Energy Scale

We follow the recommendation of jet energy correction group and use the new systematic function provided by the jet energy correction group. We vary the correction at each level by $\pm 1\sigma$ and take quadrature of differences as the systematic.

A.4 Soft Jet Modeling

The soft jets may not be simulated well in the Monte Carlo. We have used the inclusive $W^{\pm} + 0$ ($Z^0 + 0$) jet and $W^{\pm} + 1$ ($Z^0 + 1$) jet data and Monte Carlo samples to estimate the soft E_T jet rejection factors. Figure 11 shows the soft E_T jet selection efficiencies. The efficiencies are found to be 0.947 ± 0.001 (0.944 ± 0.004) and 0.882 ± 0.003 (0.902 ± 0.016) from the data and 0.933 ± 0.001 (0.930 ± 0.001) and 0.892 ± 0.004 (0.895 ± 0.003) from the Monte Carlo, respectively. We take the difference (1%) as the systematic for soft jet modeling.

A.5 Jet Energy Smearing

The studies of gamma-jet balancing indicate that jets in Pythia are 15% narrower than in the data. We have estimated the changes in the acceptance after smearing the jet energy in the Monte Carlo with additional 15% of jet energy resolution. The change is small about 1% for the systematic.

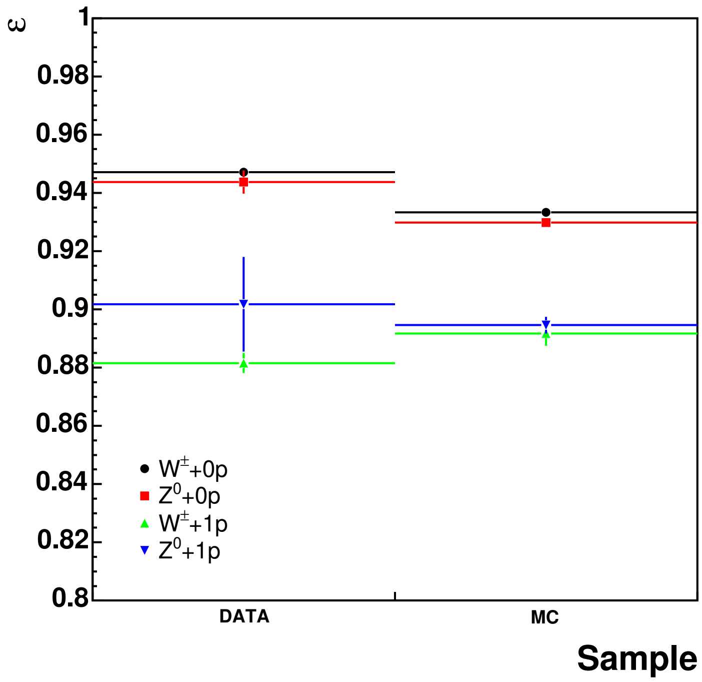


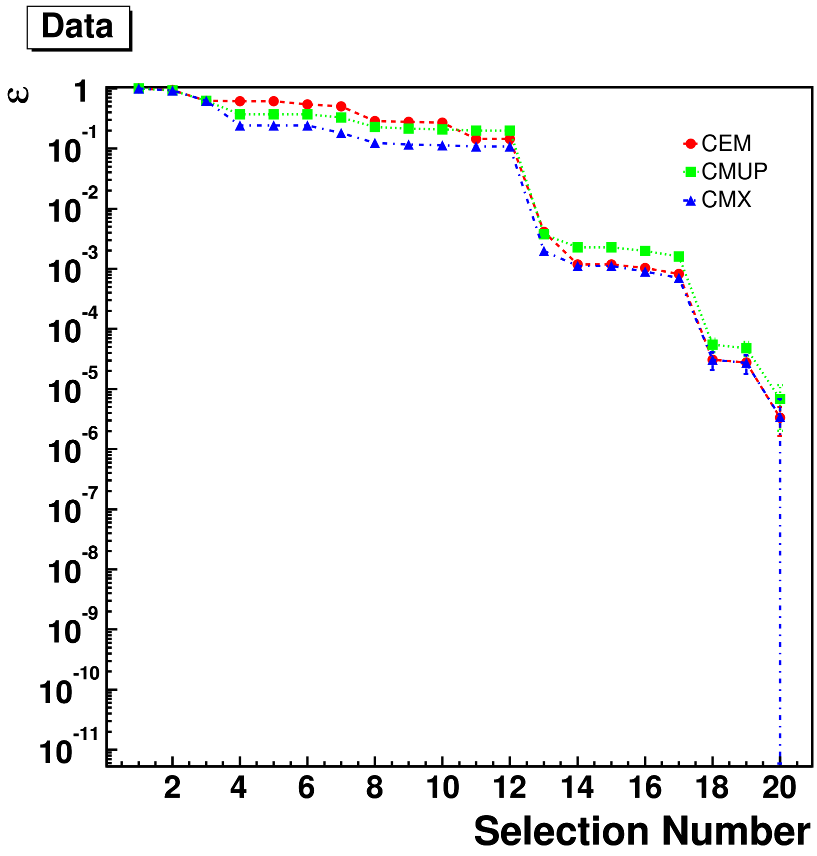
Figure 11: Extra jet selection efficiency for data and MC.

B Selection Efficiency

Upon the Godparent committee's request, we have listed the event counts and corresponding efficiency in $W^{\pm}$+2 bin after each selection cut for the data and the Monte Carlo signal and background samples.

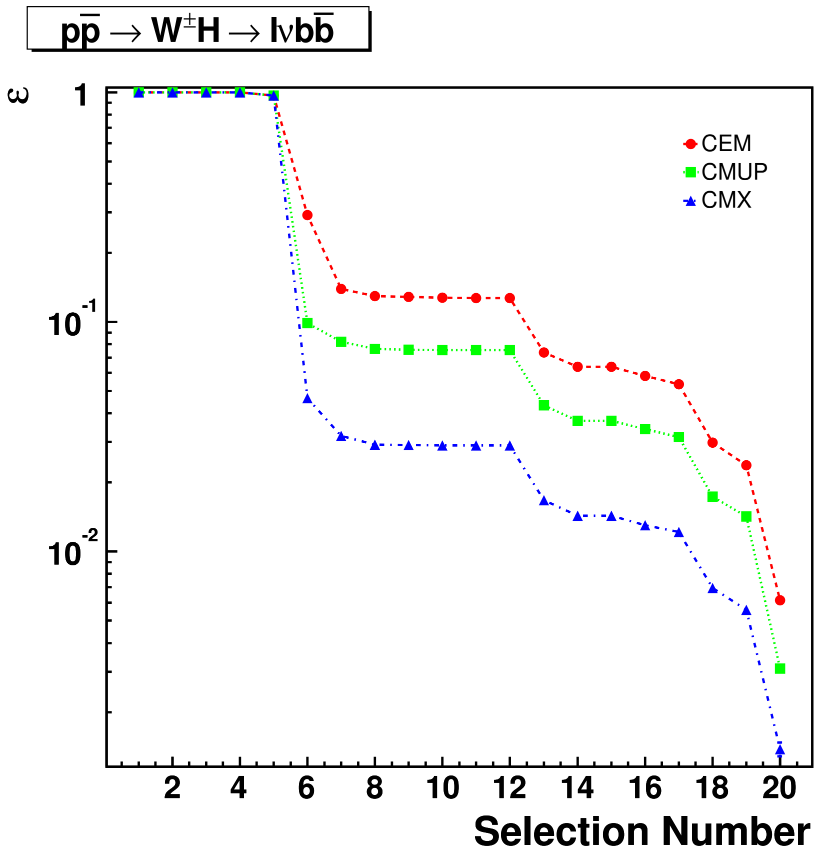
B.1 Data

Selection	CEM	CMUP	CMX
1. Initial	1201589	292125	292125
2. Good si. align.	1119032	271626	271626
3. Good run	742568	182679	182679
4. Trigger	735971	107932	70774
5. Obsp z vertex	735971	107932	70774
6. Lepton geom. ID	650447	107903	70756
7. Lepton ID	604218	95166	52883
8. Lepton Isol.	341376	66857	36073
9. !Dilepton	332953	63073	34098
10. $!Z^0$	324092	60740	32944
11. !Conv. or Cosmic	174722	58298	31815
12. !Isol. tracks	174222	58060	31700
13. # of jets = 2	4943	1102	579
14. Missing $E_T > 20$ GeV	1420	668	324
15. $E_T^{jet1} > 15$ GeV	1420	668	324
16. !# of extra jets	1229	581	262
17. At least one tagg. jets	982	470	207
18. At least one tag	37	16	9
19. Single tag	33	14	8
20. Double tag	4	2	1



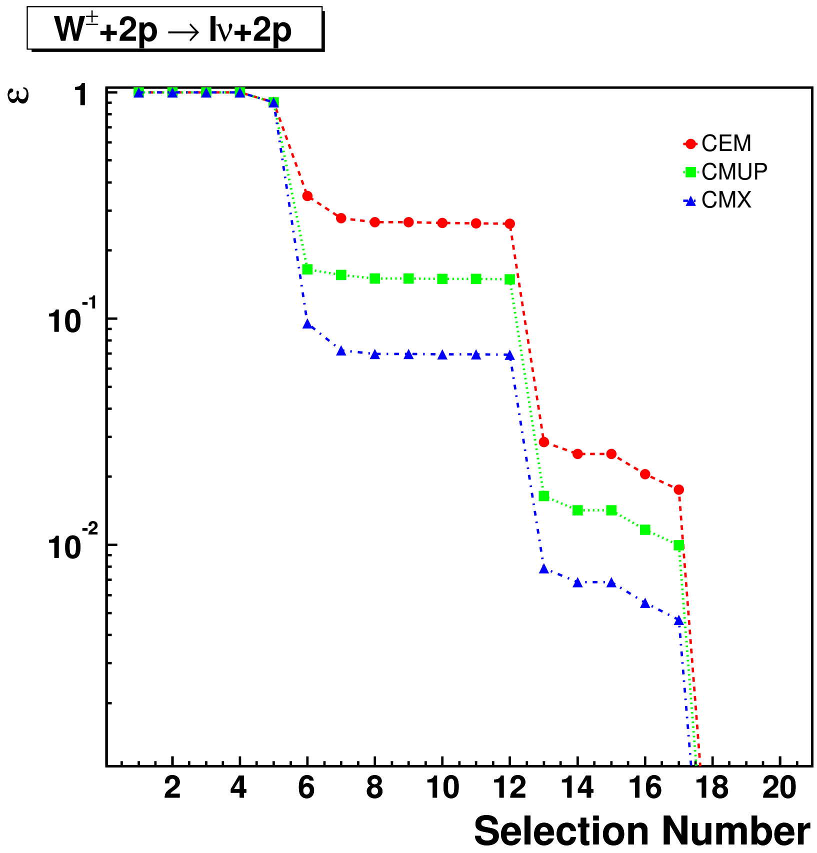
B.2 $W^{\pm}H \to \ell\nu b\bar{b}$ MC sample ($m_H = 115$ GeV/c^2)

Selection	CEM	CMUP	CMX
1. Initial	150000	150000	150000
2. Good si. align.	150000	150000	150000
3. Good run	150000	150000	150000
4. Trigger	150000	150000	150000
5. Obsp z vertex	145332	145332	145332
6. Lepton geom. ID	43764	14836	6987
7. Lepton ID.	20871	12304	4787
8. Lepton isol.	19417	11434	4391
9. !Dilepton	19280	11358	4363
10. !Z^0	19145	11314	4347
11. !conv. or cosmic	19076	11314	4347
12. !Isol. tracks	19059	11294	4344
13. # of jets == 2	10994	6438	2485
14. $\not\!\!E_T > 20$ GeV	9528	5527	2131
15. $E_T^{jet1} > 15$ GeV	9528	5527	2131
16. !Extra jets	8690	5058	1929
17. At least one tagg. jets	7973	4649	1801
18. At least one tag	4512	2579	1028
19. Single tag	3621	2084	812
20. Double tag	891	495	216



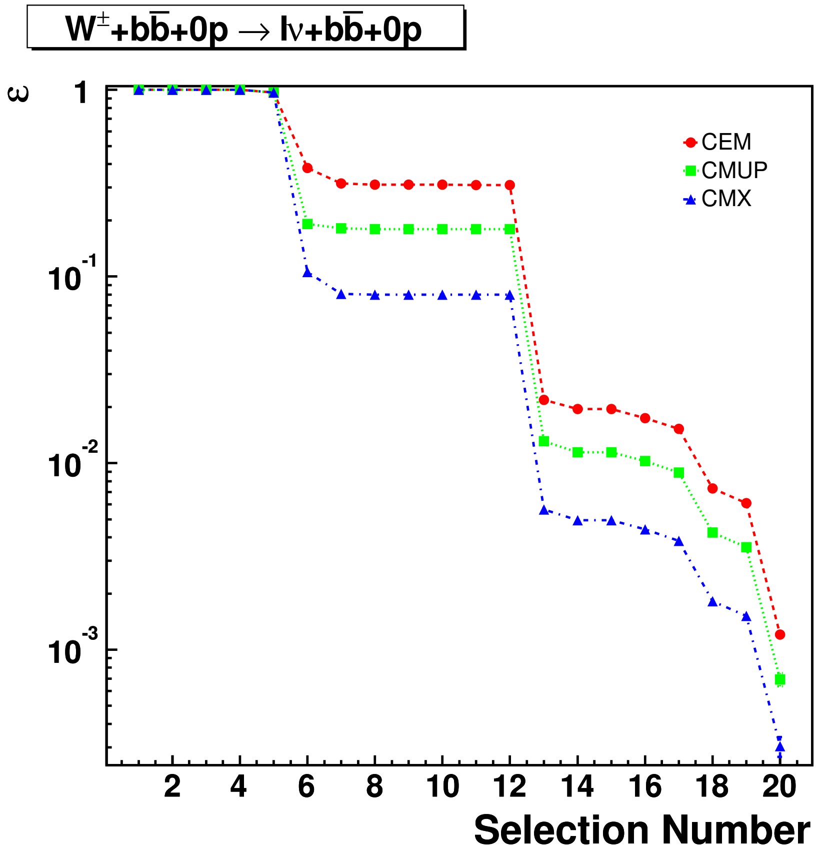
B.3 $W^\pm + 2p \to \ell\nu + 2p$

Selection	CEM	CMUP	CMX
1. Initial	189131	260000	260000
2. Good si. align.	189131	260000	260000
3. Good run	189131	260000	260000
4. Trigger	189131	260000	260000
5. Obsp z vertex	170988	234768	234768
6. Lepton geom. ID	65743	42961	24712
7. Lepton ID	52423	40510	18835
8. Lepton Isol.	50349	39005	18130
9. !Dilepton	50330	38995	18125
10. !Z^0	49954	38857	18053
11. !Conv. or Cosmic	49838	38857	18053
12. !Isol. tracks	49716	38751	18016
13. # of jets = 2	5378	4276	2050
14. Missing $E_T > 20$ GeV	4763	3690	1781
15. $E_T^{jet1} > 15$ GeV	4763	3690	1781
16. !# of extra jets	3879	3035	1445
17. At least one tagg. jets	3316	2588	1213
18. At least one tag	40	33	20
19. Single tag	39	32	20
20. Double tag	1	1	0



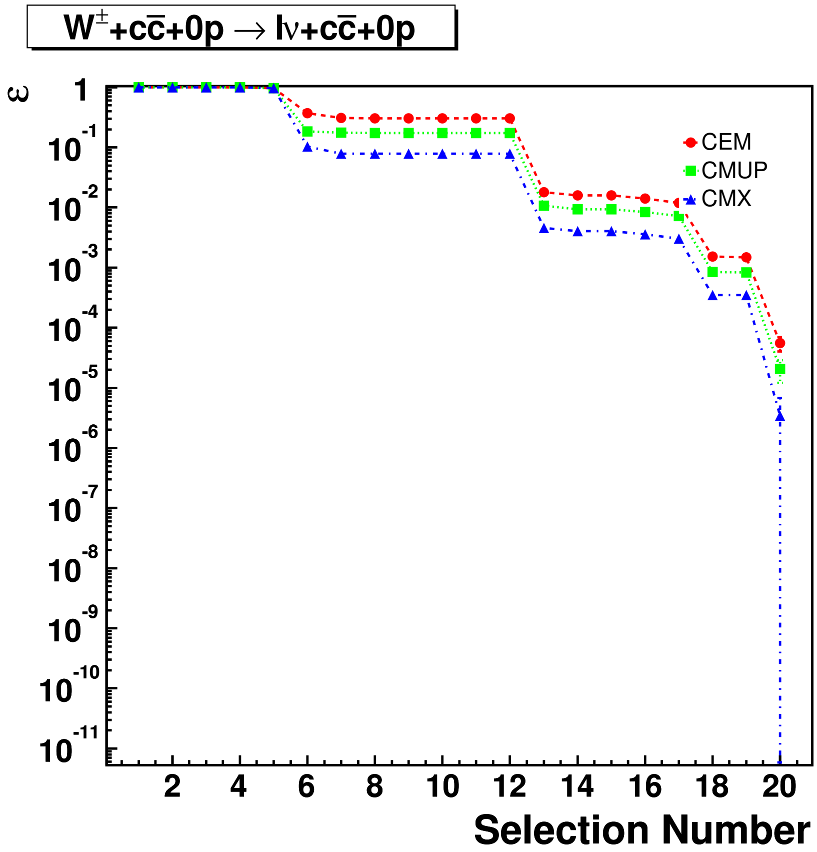
B.4 $W^{\pm} + b\bar{b} + 0p \rightarrow \ell\nu + b\bar{b} + 0p$

Selection	CEM	CMUP	CMX
1. Initial	233931	220768	220768
2. Good si. align.	233931	220768	220768
3. Good run	233931	220768	220768
4. Trigger	233931	220768	220768
5. Obsp z vertex	226125	213566	213566
6. Lepton geom. ID	89431	42286	23278
7. Lepton ID	73612	40011	17800
8. Lepton Isol.	72743	39713	17643
9. !Dilepton	72739	39712	17642
10. !Z^0	72533	39658	17617
11. !Conv. or Cosmic	72392	39658	17617
12. !Isol. tracks	72379	39648	17614
13. # of jets = 2	5090	2888	1243
14. Missing $E_T > 20$ GeV	4564	2527	1089
15. $E_T^{jet1} > 15$ GeV	4564	2527	1089
16. !# of extra jets	4069	2263	976
17. At least one tagg. jets	3563	1960	844
18. At least one tag	1709	936	402
19. Single tag	1427	783	335
20. Double tag	282	153	67



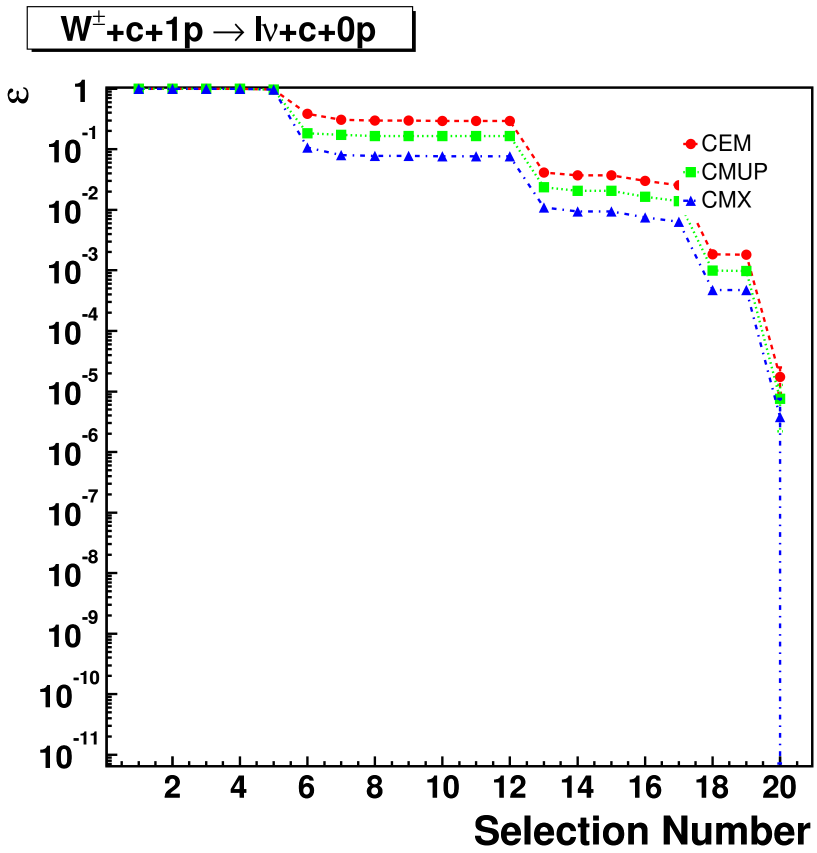
B.5 $W^{\pm} + c\bar{c} + 0p \to \ell\nu + c\bar{c} + 0p$

Selection	CEM	CMUP	CMX
1. Initial	252902	293029	293029
2. Good si. align.	252902	293029	293029
3. Good run	252902	293029	293029
4. Trigger	252902	293029	293029
5. Obsp z vertex	244351	283361	283361
6. Lepton geom. ID	94219	54260	30089
7. Lepton ID	78055	51443	23100
8. Lepton Isol.	77180	51110	22888
9. !Dilepton	77173	51108	22886
10. !Z^0	76931	51025	22846
11. !Conv. or Cosmic	76763	51025	22846
12. !Isol. tracks	76749	51009	22839
13. # of jets = 2	4509	3118	1334
14. Missing $E_T > 20$ GeV	4018	2730	1183
15. $E_T^{jet1} > 15$ GeV	4018	2730	1183
16. !# of extra jets	3548	2472	1052
17. At least one tagg. jets	3024	2098	883
18. At least one tag	387	249	103
19. Single tag	373	243	102
20. Double tag	14	6	1



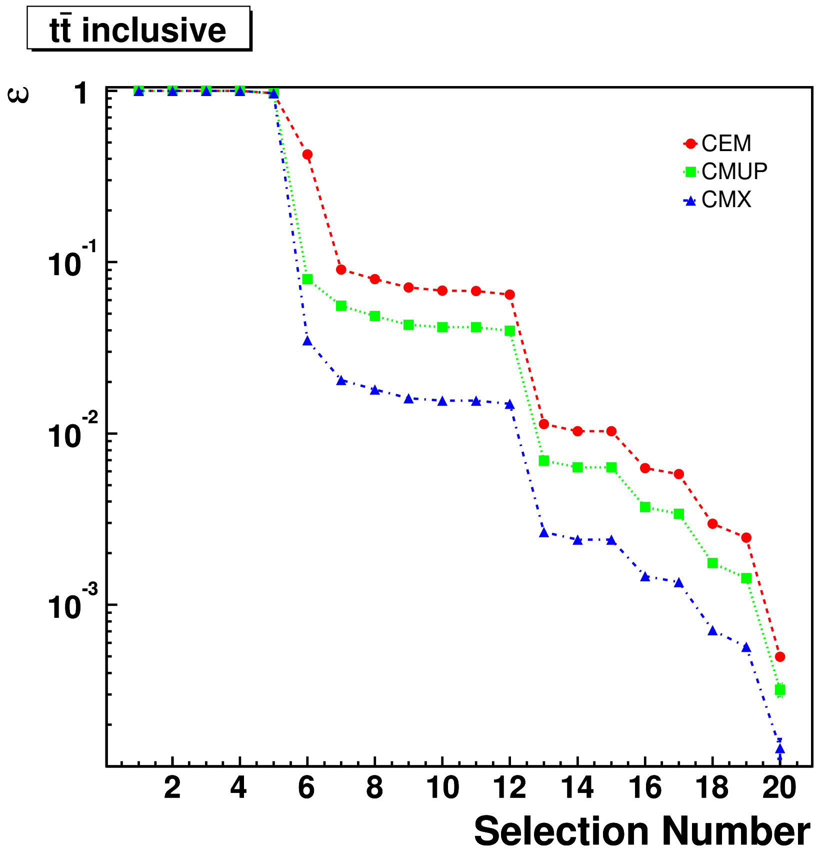
B.6 $W^{\pm} + c + 1p \to \ell\nu + c + 0p$

Selection	CEM	CMUP	CMX
1. Initial	290046	264995	264995
2. Good si. align.	290046	264995	264995
3. Good run	290046	264995	264995
4. Trigger	290046	264995	264995
5. Obsp z vertex	280676	256436	256436
6. Lepton geom. ID	111791	48589	28144
7. Lepton ID	89460	45750	21275
8. Lepton Isol.	85872	44006	20473
9. !Dilepton	85848	43996	20469
10. $!Z^0$	85118	43837	20378
11. !Conv. or Cosmic	84903	43837	20378
12. !Isol. tracks	84745	43749	20346
13. # of jets = 2	12030	6225	2880
14. Missing $E_T > 20$ GeV	10810	5472	2507
15. $E_T^{jet1} > 15$ GeV	10810	5472	2507
16. !# of extra jets	8678	4336	1979
17. At least one tagg. jets	7351	3677	1692
18. At least one tag	530	261	126
19. Single tag	525	259	125
20. Double tag	5	2	1



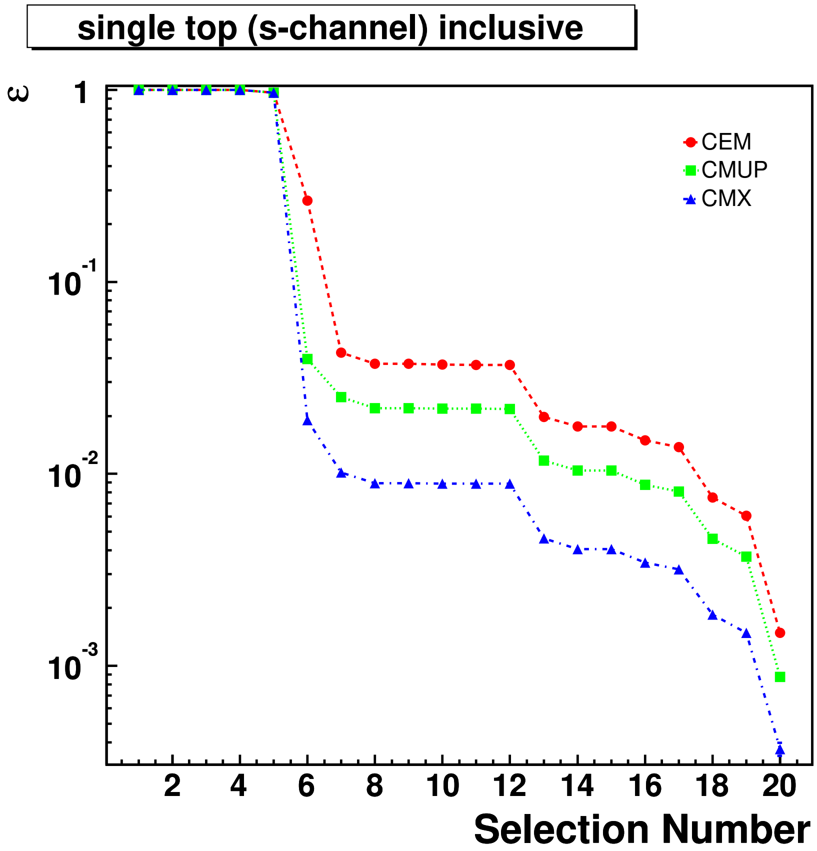
B.7 $t\bar{t}$ inclusive

Selection	CEM	CMUP	CMX
1. Initial	398037	398037	398037
2. Good si. align.	398037	398037	398037
3. Good run	398037	398037	398037
4. Trigger	398037	398037	398037
5. Obsp z vertex	384875	384875	384875
6. Lepton geom. ID	169223	31688	13890
7. Lepton ID	36048	22129	8154
8. Lepton Isol.	31685	19281	7183
9. !Dilepton	28389	17112	6392
10. !Z^0	27122	16576	6196
11. !Conv. or Cosmic	26988	16576	6196
12. !Isol. tracks	25708	15834	5924
13. # of jets = 2	4520	2763	1059
14. Missing $E_T > 20$ GeV	4113	2520	958
15. $E_T^{jet1} > 15$ GeV	4113	2520	958
16. !# of extra jets	2493	1481	584
17. At least one tagg. jets	2304	1349	539
18. At least one tag	1182	697	284
19. Single tag	984	570	226
20. Double tag	198	127	58



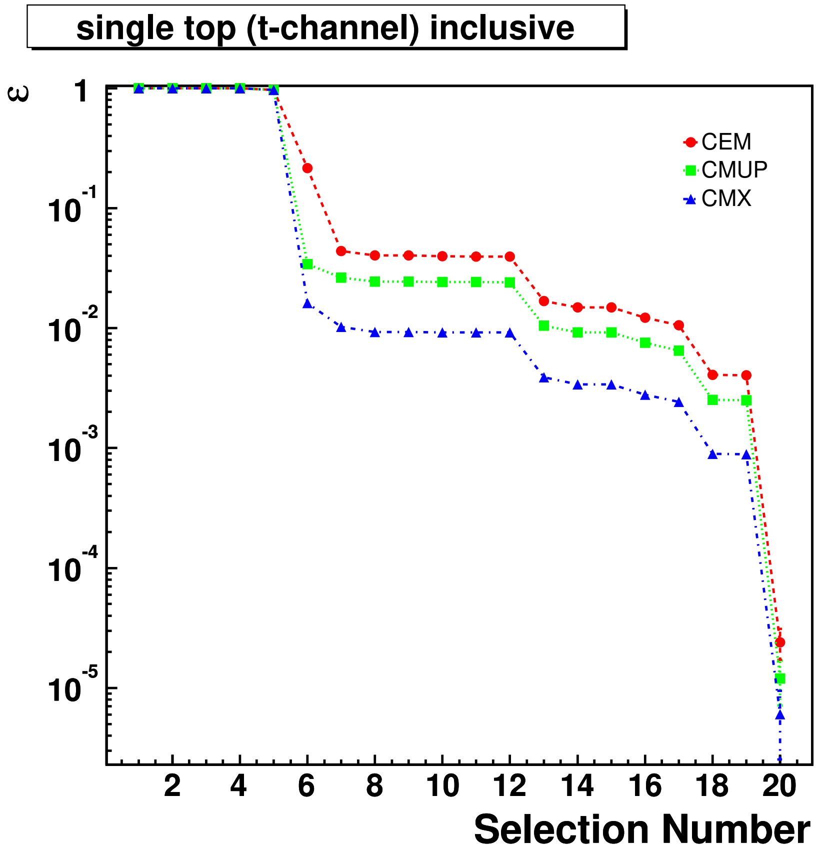
B.8 single top (s-channel) inclusive

Selection	CEM	CMUP	CMX
1. Initial	440000	440000	440000
2. Good si. align.	440000	440000	440000
3. Good run	440000	440000	440000
4. Trigger	440000	440000	440000
5. Obsp z vertex	425541	425541	425541
6. Lepton geom. ID	116601	17417	8367
7. Lepton ID	18778	11024	4472
8. Lepton Isol.	16451	9648	3934
9. !Dilepton	16441	9646	3933
10. !Z^0	16309	9607	3914
11. !Conv. or Cosmic	16243	9607	3914
12. !Isol. tracks	16227	9593	3911
13. # of jets = 2	8687	5160	2029
14. Missing $E_T > 20$ GeV	7746	4568	1786
15. $E_T^{jet1} > 15$ GeV	7746	4568	1786
16. !# of extra jets	6582	3857	1517
17. At least one tagg. jets	6048	3549	1399
18. At least one tag	3315	2015	814
19. Single tag	2663	1629	652
20. Double tag	652	386	162



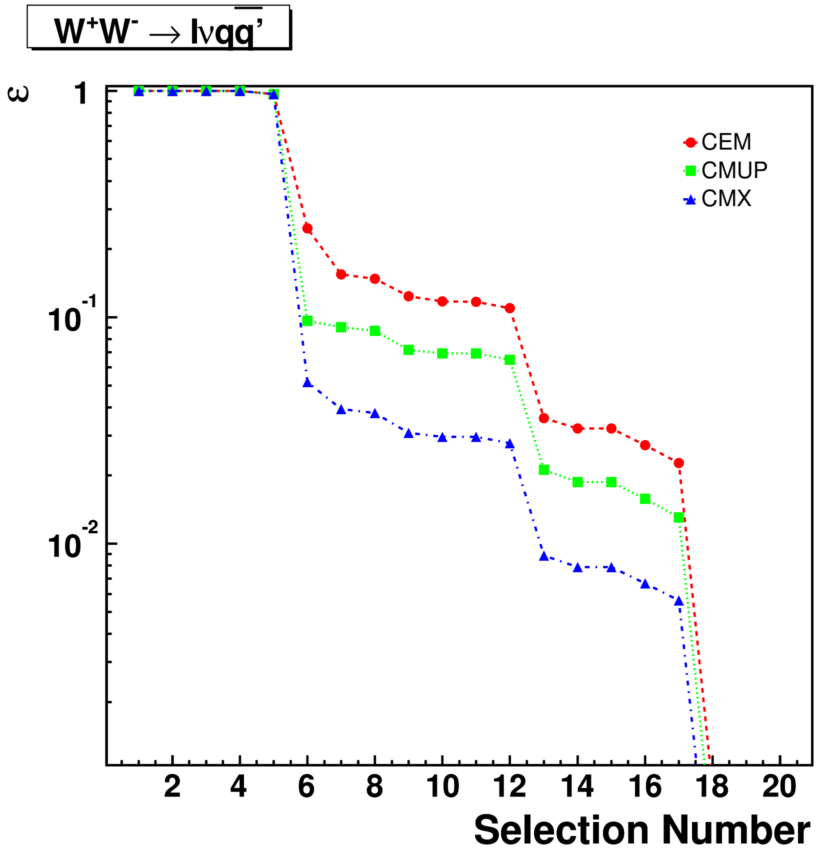
B.9 single top (t-channel) inclusive

Selection	CEM	CMUP	CMX
1. Initial	499189	499189	499189
2. Good si. align.	499189	499189	499189
3. Good run	499189	499189	499189
4. Trigger	499189	499189	499189
5. Obsp z vertex	482770	482770	482770
6. Lepton geom. ID	108256	17044	8054
7. Lepton ID	21915	13161	5103
8. Lepton Isol.	20128	12157	4630
9. !Dilepton	20112	12153	4622
10. $!Z^0$	19834	12061	4598
11. !Conv. or Cosmic	19743	12061	4598
12. !Isol. tracks	19673	12022	4582
13. # of jets = 2	8416	5233	1940
14. Missing $E_T > 20$ GeV	7459	4606	1699
15. $E_T^{jet1} > 15$ GeV	7459	4606	1699
16. !# of extra jets	6119	3769	1389
17. At least one tagg. jets	5288	3235	1210
18. At least one tag	2035	1256	445
19. Single tag	2023	1250	442
20. Double tag	12	6	3



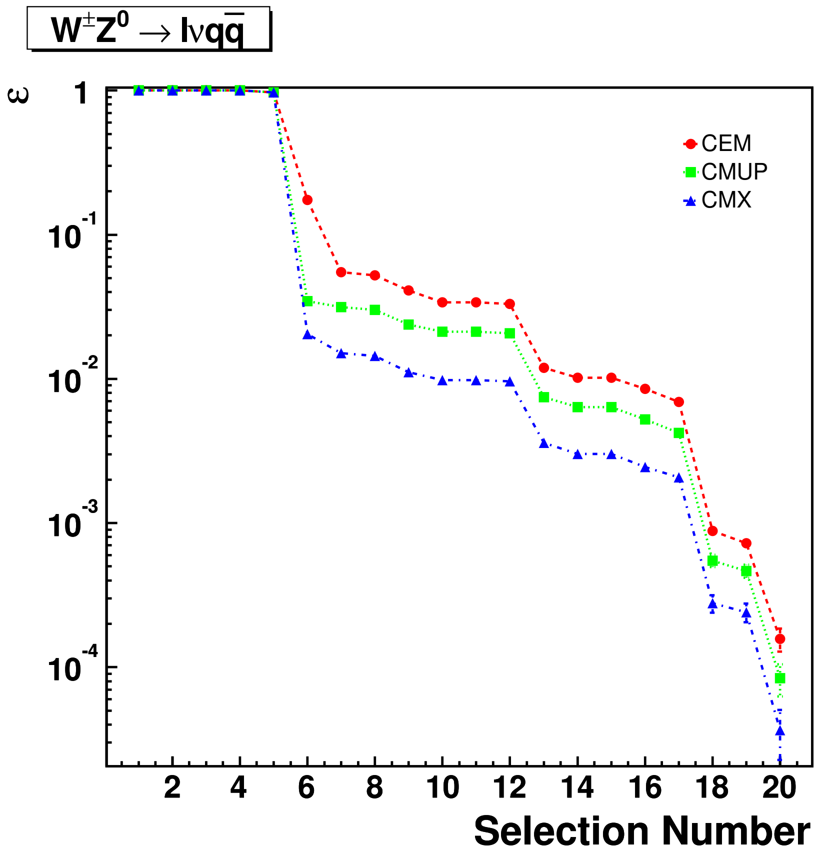
B.10 $W^+W^- \to \ell\nu q\bar{q}'$

Selection	CEM	CMUP	CMX
1. Initial	934969	934969	934969
2. Good si. align.	934969	934969	934969
3. Good run	934969	934969	934969
4. Trigger	934969	934969	934969
5. Obsp z vertex	904122	904122	904122
6. Lepton geom. ID	231322	90112	48327
7. Lepton ID	144631	84641	36750
8. Lepton Isol.	138428	81309	35296
9. !Dilepton	115932	67087	28869
10. $!Z^0$	109846	64790	27747
11. !Conv. or Cosmic	109496	64790	27747
12. !Isol. tracks	102374	60557	25972
13. # of jets = 2	33450	19795	8300
14. Missing $E_T > 20$ GeV	30128	17466	7367
15. $E_T^{jet1} > 15$ GeV	30128	17466	7367
16. !# of extra jets	25419	14753	6257
17. At least one tagg. jets	21224	12200	5246
18. At least one tag	793	465	219
19. Single tag	788	465	218
20. Double tag	5	0	1



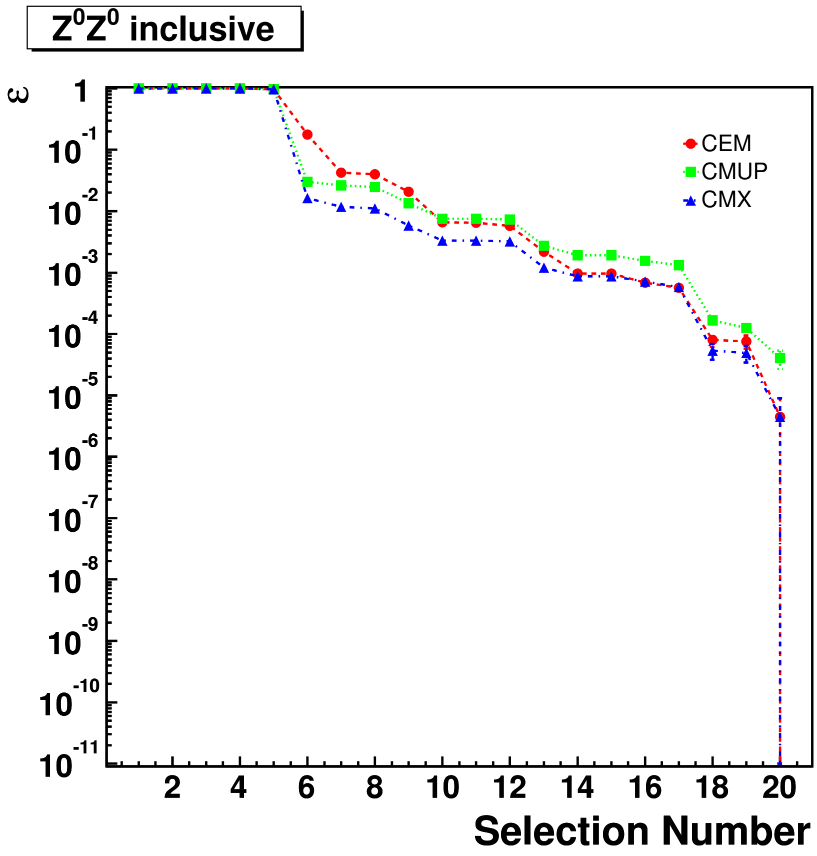
B.11 $W^{\pm}Z^0 \to \ell\nu q\bar{q}$

Selection	CEM	CMUP	CMX
1. Initial	191011	191011	191011
2. Good si. align.	191011	191011	191011
3. Good run	191011	191011	191011
4. Trigger	191011	191011	191011
5. Obsp z vertex	184934	184934	184934
6. Lepton geom. ID	33285	6599	3906
7. Lepton ID	10489	5993	2872
8. Lepton Isol.	9973	5754	2755
9. !Dilepton	7819	4551	2127
10. $!Z^0$	6501	4044	1870
11. !Conv. or Cosmic	6466	4044	1870
12. !Isol. tracks	6340	3965	1838
13. # of jets = 2	2274	1428	686
14. Missing $E_T > 20$ GeV	1946	1215	576
15. $E_T^{jet1} > 15$ GeV	1946	1215	576
16. !# of extra jets	1625	997	466
17. At least one tagg. jets	1325	807	397
18. At least one tag	168	105	53
19. Single tag	138	89	46
20. Double tag	30	16	7



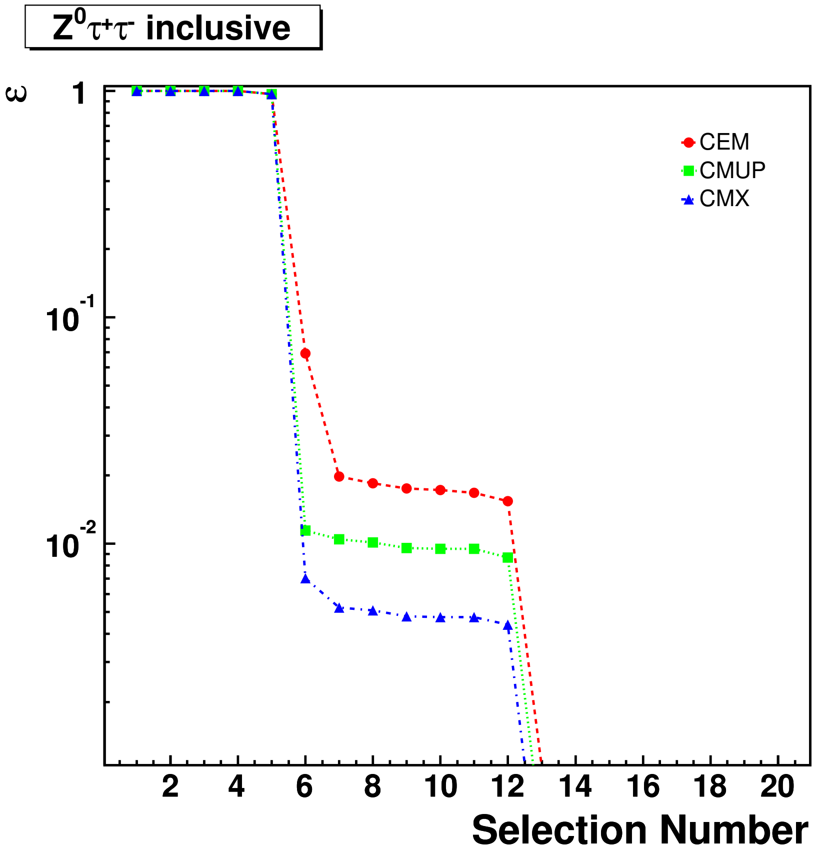
B.12 Z^0Z^0 inclusive

Selection	CEM	CMUP	CMX
1. Initial	223606	223606	223606
2. Good si. align.	223606	223606	223606
3. Good run	223606	223606	223606
4. Trigger	223606	223606	223606
5. Obsp z vertex	216547	216547	216547
6. Lepton geom. ID	39890	6706	3679
7. Lepton ID	9418	5853	2614
8. Lepton Isol.	8875	5568	2473
9. !Dilepton	4656	2990	1298
10. !Z^0	1467	1696	745
11. !Conv. or Cosmic	1443	1696	745
12. !Isol. tracks	1287	1630	718
13. # of jets = 2	490	608	271
14. Missing $E_T > 20$ GeV	215	425	193
15. $E_T^{jet1} > 15$ GeV	215	425	193
16. !# of extra jets	154	348	161
17. At least one tagg. jets	127	295	130
18. At least one tag	18	37	12
19. Single tag	17	28	11
20. Double tag	1	9	1



B.13 $Z^0\tau^+\tau^-$ inclusive

Selection	CEM	CMUP	CMX
1. Initial	497415	497415	497415
2. Good si. align.	497415	497415	497415
3. Good run	497415	497415	497415
4. Trigger	497415	497415	497415
5. Obsp z vertex	481010	481010	481010
6. Lepton geom. ID	34399	5683	3499
7. Lepton ID	9830	5196	2602
8. Lepton Isol.	9182	5037	2524
9. !Dilepton	8731	4755	2379
10. !Z^0	8599	4716	2361
11. !Conv. or Cosmic	8346	4716	2361
12. !Isol. tracks	7674	4316	2185
13. # of jets = 2	514	261	128
14. Missing $E_T > 20$ GeV	141	93	48
15. $E_T^{jet1} > 15$ GeV	141	93	48
16. !# of extra jets	117	80	39
17. At least one tagg. jets	88	67	30
18. At least one tag	5	2	1
19. Single tag	5	2	1
20. Double tag	0	0	0



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[3] Henri Bachacou, Ken Bloom, Koji Ebina, Nathan Goldschmidt, Jian Kang, Andrea Messina, Valentin Necula, Koji Sato, Evelyn Thomson, Rocio Vilar, Peter Wittich, Kohei Yorita $t\bar{t}$ Event Selection and Detection Efficiency for Winter 2003 Lepton + Jets Analysis, CDF Note 6084.
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