SEARCH FOR THE HIGGS BOSON AT CDF RUN II

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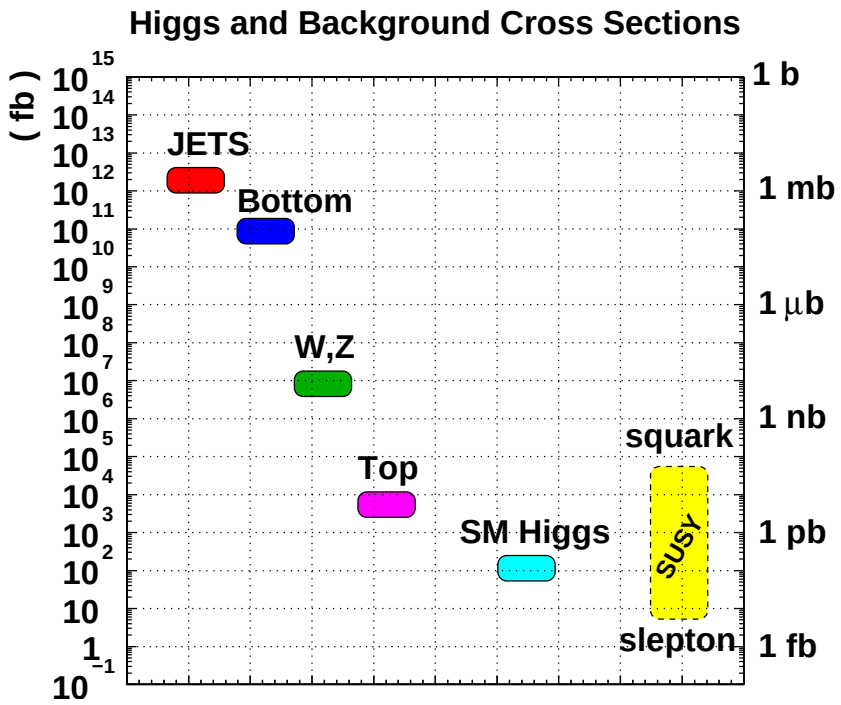
Contents

Introduction - Motivation

- **Standard Model is an *effective* theory of particle physics up to the electroweak scale O (100 GeV),**
- **Standard Model predicts the existence of Higgs boson and requires "new physics" to stabilize the Higgs mass,**
- **Possible source of new physics:**
  - **SUSY and its variants,**
  - ***Extra*-dimensions,**
  - **Little Higgs,**
  - **Higgsless ...**
- **Need experimental inputs for the future direction !!**

Introduction - Typical Cross Section

Typical Cross Section in $p\bar{p}$ Collider

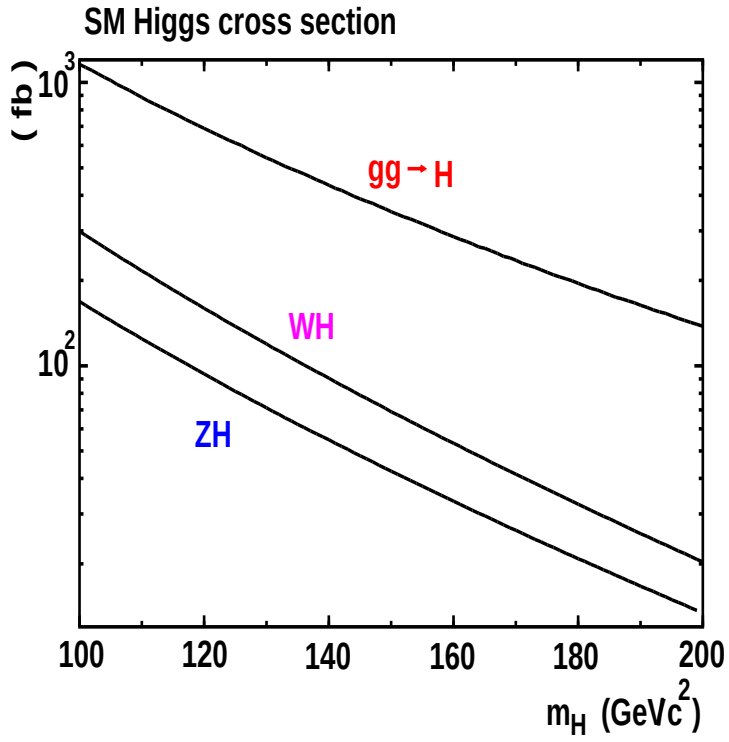


Physics in $p\bar{p}$ Collider

- Start $p\bar{p}$ inelastic scattering: 60 mb,
- QCD JETS physics: mb order,
- Electroweak physics: nb order,
- Top pair production cross section: $\sim$ 6 pb,
- SM Higgs production cross section: $\sim 10^2$ fb.
- Change 10 orders of magnitude!!

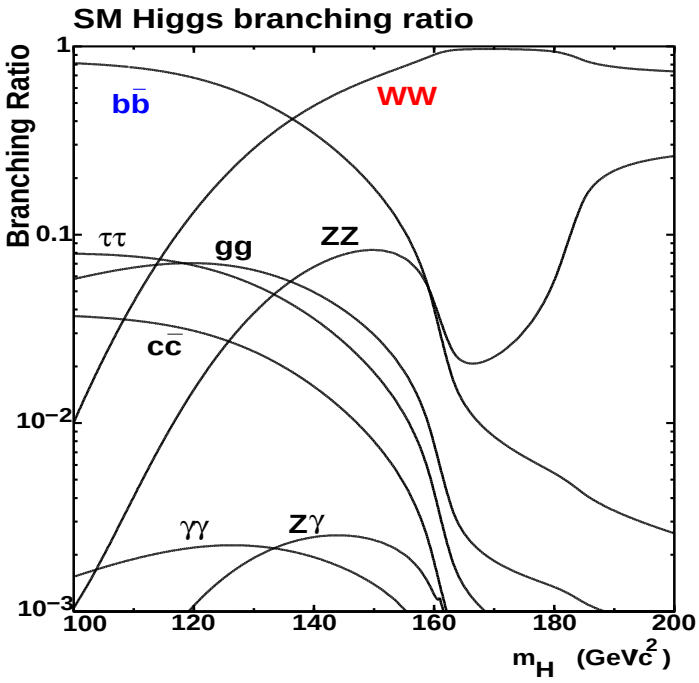
Introduction - SM Higgs Production

SM Higgs Production Cross Section



- Three paths of the Higgs boson production
- $gg \to H$:
  dominates but dijet background too big,
- $q\bar{q}' \to WH$, ZH :
  Most accessible, easy to trigger,
  WH+$ZH \sim$ 300 fb (115 GeV),
  90 fb (160 GeV).

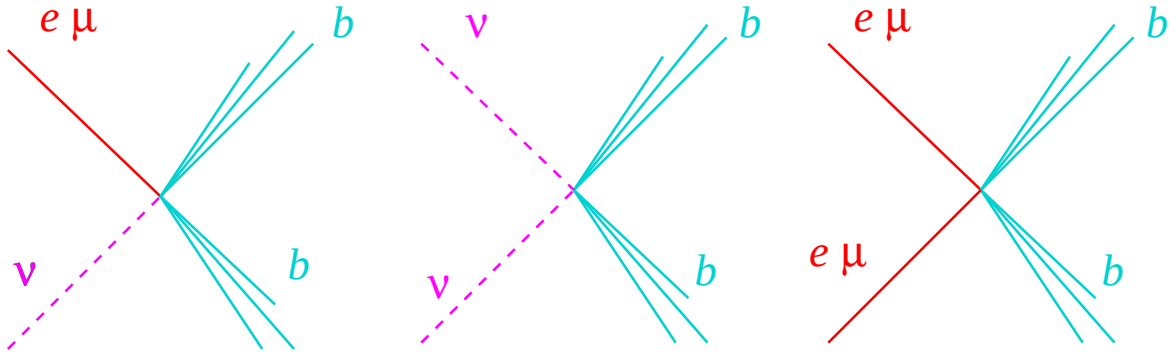
SM Higgs Decay Branching Ratios: $H \to XX$



- $M_{\rm H} < 135$ GeV/c^2 : $H \to b\bar{b}$
  - Excellent b-tag efficiency,
  - Di-jet mass resolution.
- $M_{\rm H} \geq 135$ GeV/c^2 : $H \to WW$
  - Exploit the large $\sigma(gg \to H)$,
  - Identify clean final states with leptons.
- Very Challenging at Tevatron ...

Introduction - Promising Signature

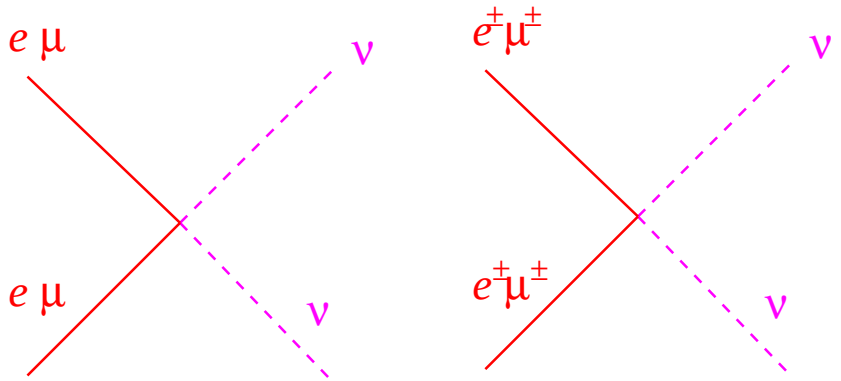
- **For $M_{\mathrm{H}} < 135$ GeV:**



$WH \to l\nu bb$ $\quad$ $ZH \to \nu\nu bb$ $\quad$ $ZH \to llbb$

$\ell + \not\!\!E_T + b\bar{b}$, $\quad$ $\not\!\!E_T + b\bar{b}$, $\quad$ **or** $\quad$ **OS** $\ell\ell + b\bar{b}$

- **For $M_{\mathrm{H}} \geq 135$ GeV:**

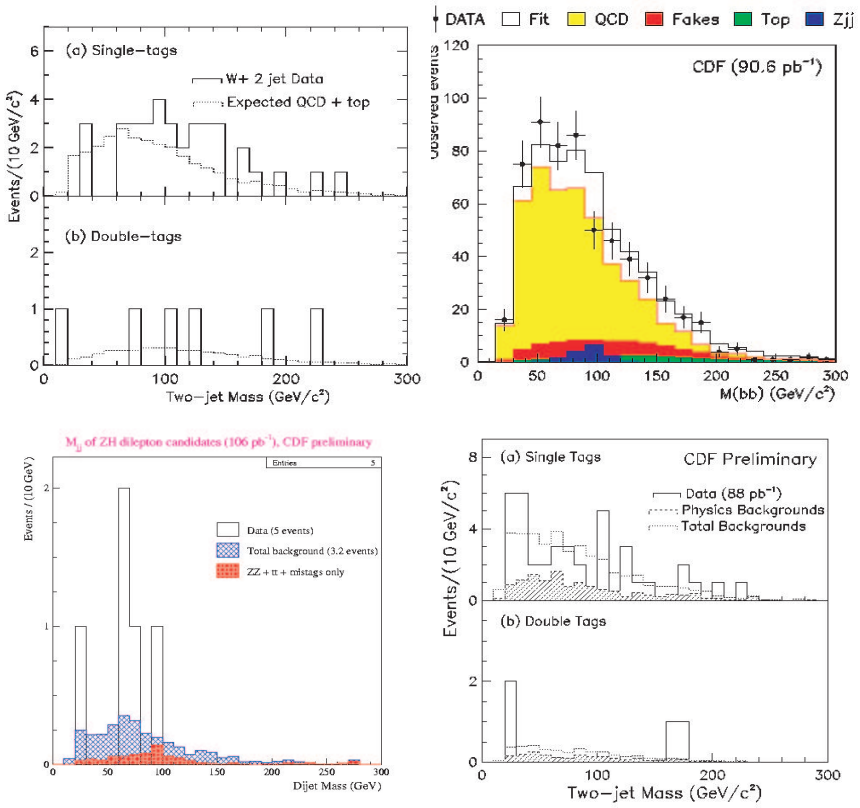


$gg \to H \to WW \to l\nu l\nu$ $\quad$ $WH \to WWW \to l^{\pm}\nu l^{\pm}\nu qq$

OS $\ell\ell + \not\!\!E_T$ $\quad$ **or** $\quad$ **Like-Sign** $\ell\ell + \not\!\!E_T$

Introduction - Run I VH searches (106 pb^{-1})

Higgs mass distributions

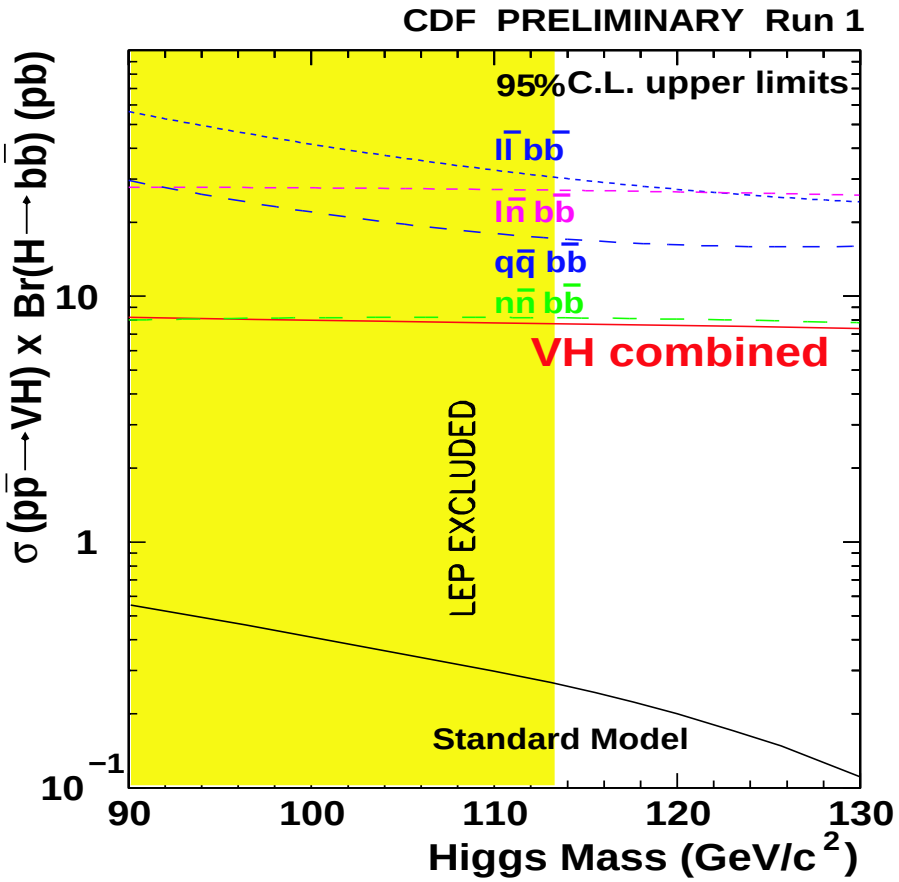


Expected and Observed events

- **Set $\sigma_{\rm VH} \cdot Br <$ 8 pb at 95 % C.L. ,**
- $WH \to \ell\nu + b\bar{b}$,
  Exp: 30 $\pm$ 5, (single tags)
  Obs: 36,
  Exp: 6 $\pm$ 0.6, (double tags)
  Obs: 6,
- $WH \to \ell\nu + q\bar{q}$,
  Exp: 600,
  Obs: 580,
- $ZH \to \ell^+\ell^- + b\bar{b}$,
  Exp: 3.2 $\pm$ 0.7,
  Obs: 5,
- $ZH \to \nu\bar{\nu} + b\bar{b}$,
  Exp: 39.2 $\pm$ 4.4, (single tags)
  Obs: 40,
  Exp: 3.9 $\pm$ 0.6, (double tags)
  Obs: 4,

Introduction - SM Higgs searches

SM Higgs Searches



Mass Region

- $M_{\mathrm{H}} = 117^{+67}_{-45}$ ($M_{\mathrm{top}} = 178.0 \pm 4.3$ GeV/c^2),
- $M_{\mathrm{H}} < 251$ GeV/c^2 at 95 % C.L.,
- LEP excludes $M_{\mathrm{H}} \leq 114.4$ GeV/c^2 at 95 % C.L.

Tevatron CDF Run I

- Set $\sigma_{\mathrm{VH}} \cdot Br <$ 8 pb at 95 % C.L. ,
  $WH \rightarrow (\ell\nu,\ q\bar{q}) + b\bar{b}$,
  $ZH \rightarrow (\ell^+\ell^-,\ \nu\bar{\nu}) + b\bar{b}$,

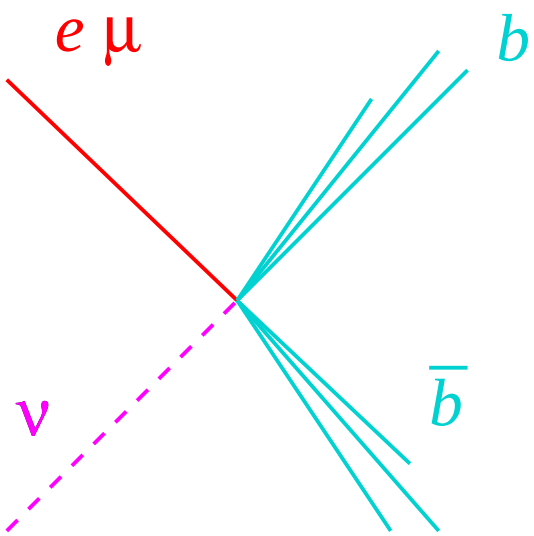
Tevatron CDF Run II

- $WH \rightarrow \ell\nu + b\bar{b}$ ($\sigma_{\mathrm{WH}} \cdot Br <$ 5 pb),
- $gg \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\nu$, ($\sigma_{\mathrm{gg\rightarrow H}} \cdot Br <$ 6 pb),
- $WH \rightarrow WWW \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu + qq$ ($\sigma_{\mathrm{WH}} \cdot Br <$ 8 pb).

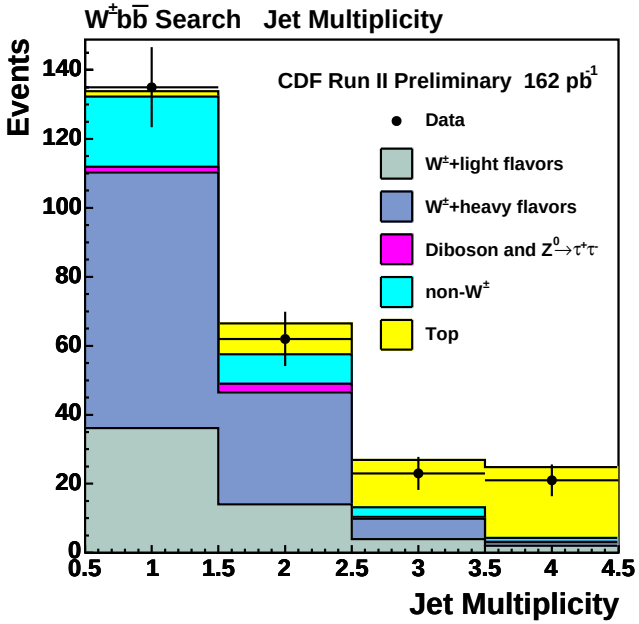
Recent CDF Run II Results

- **Re-established the top signal in lepton+jets and dilepton events using ...**
  1. **lepton identification,**
  2. **heavy-flavor tagging,**
  3. **jet energy scale.**
- **Higgs boson searches still at the engineering stage,**
- **SM Higgs boson searches - Very challenging,**
  - $WH \rightarrow \ell\nu b\bar{b}$ **: lepton + jets signature,**
  - $ZH \rightarrow \nu\nu b\bar{b}$ **:** $\not\!\!E_T$**+ jets,**
  - $gg \rightarrow H \rightarrow WW$ **: high-**p_T **Opposite-Sign dilepton +** $\not\!\!E_T$**,**
  - $WH \rightarrow WWW$ **: high-**p_T **Like-Sign dilepton +** $\not\!\!E_T$**,**
- **MSSM Searches**
  - $A/H/h \rightarrow b\bar{b}, \tau\bar{\tau}$ **: multi b-jets or ditau,**

Search for the $WH \to \ell\nu b\bar{b}$



$WH \to l\nu b\bar{b}$

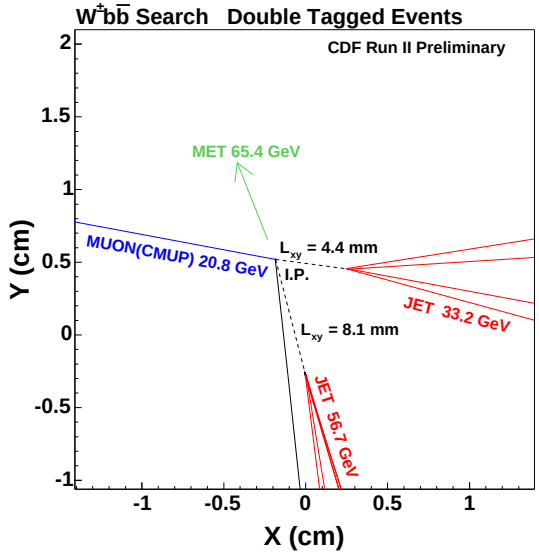


Signature

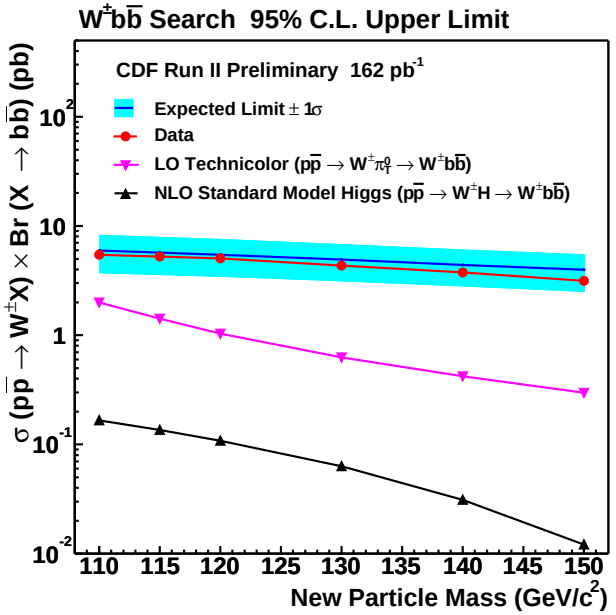
- Exact one tight lepton (e/μ) with $p_T > 20$ GeV,
- $\not\!\!E_T > 20$ GeV,
- Exact 2 jets at least one b-tagged jet,
- Extra lepton or jet veto to reduce $t\bar{t}$ background,
- Number of jets distribution was consistent with expected background.

Search for the $WH \to \ell\nu b\bar{b}$ - contd

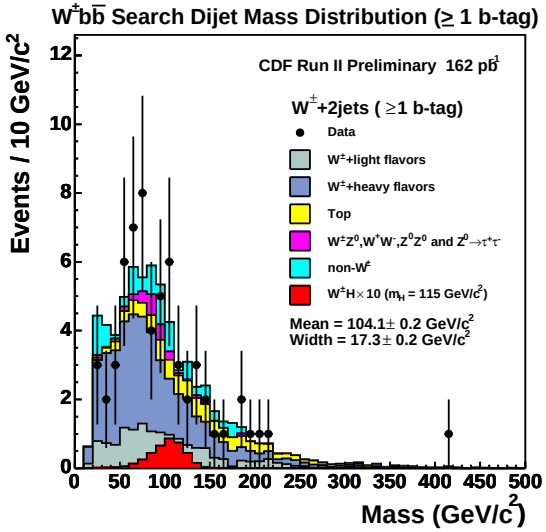
Event display



Cross section limit

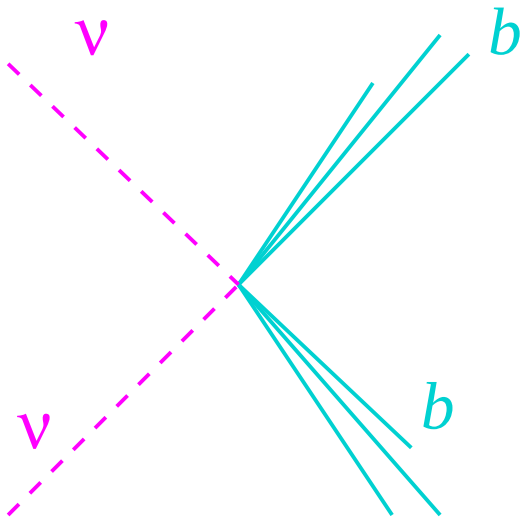


Dijet mass

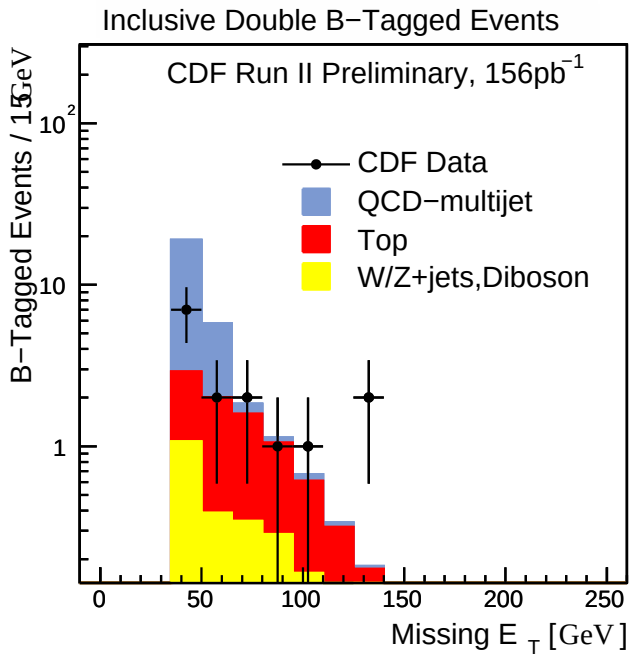


- **Set a limit on $\sigma_{\mathrm{WH}} \times Br(H \to b\bar{b})$ using dijet mass distribution,**
- **Not sensitive to SM Higgs boson yet,**
- **$\sigma_{\mathrm{WH}} \times Br(H \to b\bar{b}) <$ 5 pb at $M_{\mathrm{Higgs}} = 115$ GeV.**

Search for the $ZH \to \nu\nu b\bar{b}$



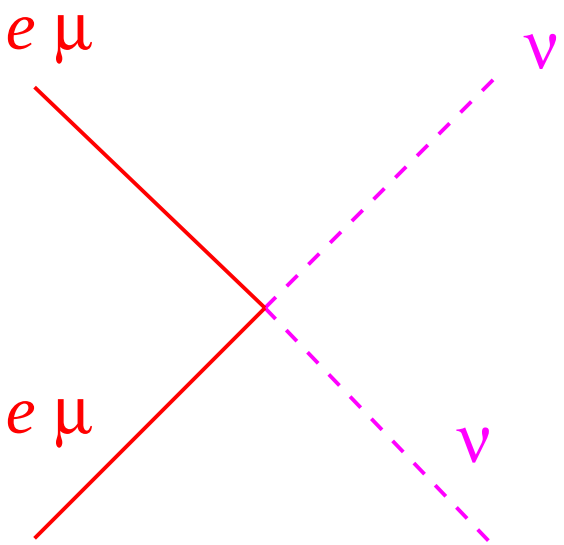
$ZH \to \nu\nu bb$



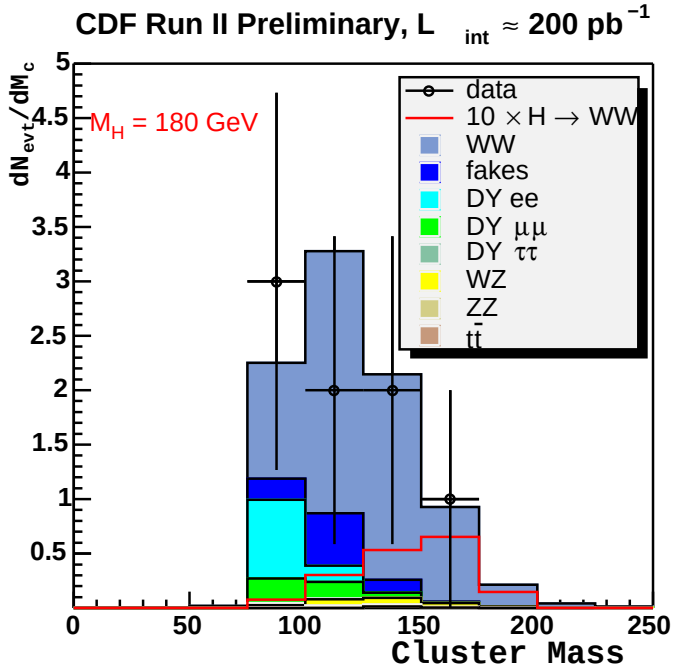
Signature

- Use ZH production,
- Select events with large $\not\!\!E_T$ and two b-tagged jets,
- Large dijet backgrounds, but less top contributions,
- Key is to understand the QCD background,
- Most sensitivity channel,
- Limit is in progress ...

Search for the $gg \to H \to W^-W^+ \to \ell^-\bar{\nu}\ell^+\nu$



$gg \to H \to WW \to l\nu l\nu$



Signature

- **Take full advantage of large** $\sigma(gg \to H)$,
- **Opposite-Sign dilepton +** $\not\!\!E_T$,
- **Tendency of collinearity of dilepton from decay of Higgs boson,**
  - **Small dilepton invariant mass,**
  - **Small dilepton angular separation.**

Cluster mass

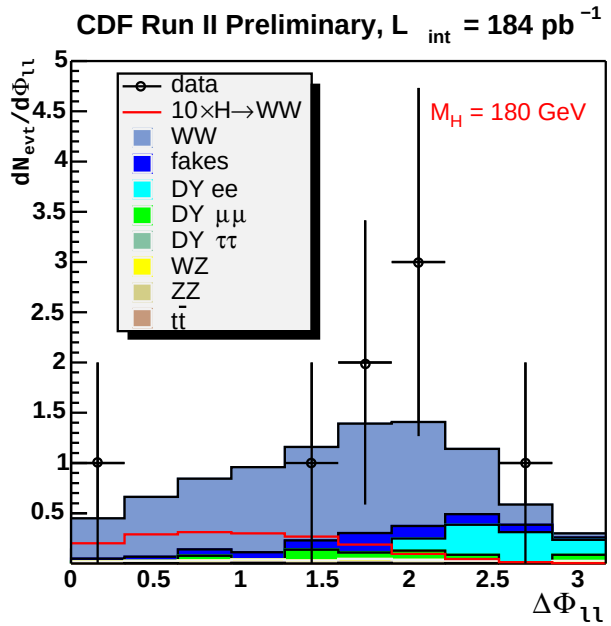
$$M_c = \sqrt{p_{T\ell\ell} + M_{\ell\ell}} + \not\!\!E_T$$

Background

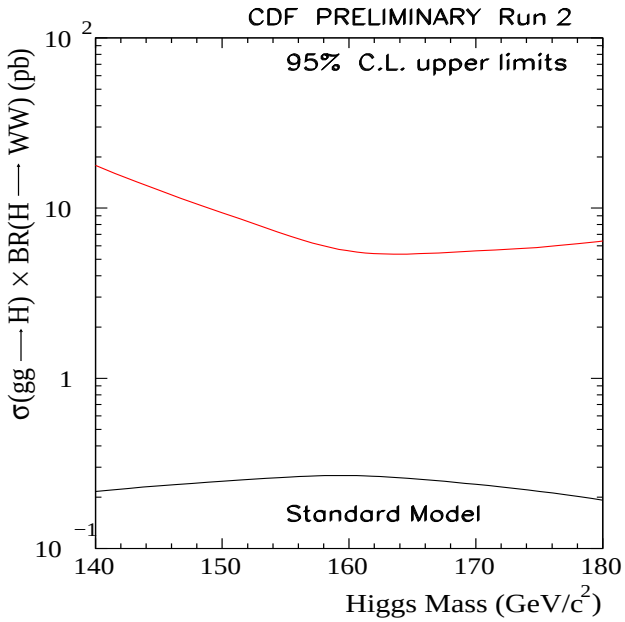
- **Electroweak** WW,
- W **+ fake lepton,**
- **Drell-Yan.**

Search for the $gg \to H \to W^-W^+ \to \ell^-\bar{\nu}\ell^+\nu$ - contd

Dilepton opening angle

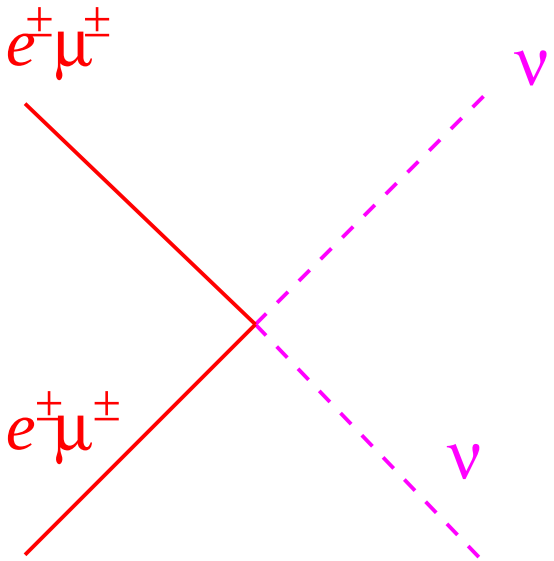


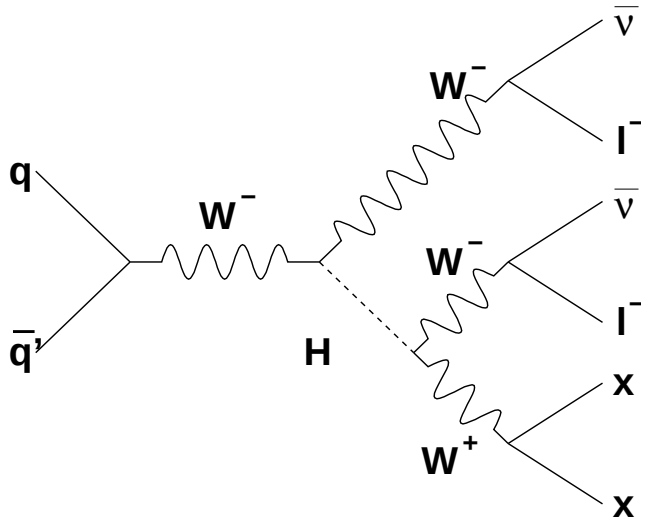
Cross section limit



- **Set a limit on** $\sigma(gg \to H) \times Br(H \to WW)$ **using dilepton opening angle distribution,**
- $\sigma(gg \to H) \times Br(H \to WW) <$ **6 pb at** $M_{\text{Higgs}} = 160$ **GeV.**

Search for the $WH \rightarrow WWW \rightarrow$ Like-Sign dilepton





$WH \rightarrow WWW \rightarrow l^{\pm}\nu l^{\pm}\nu qq$

Signature

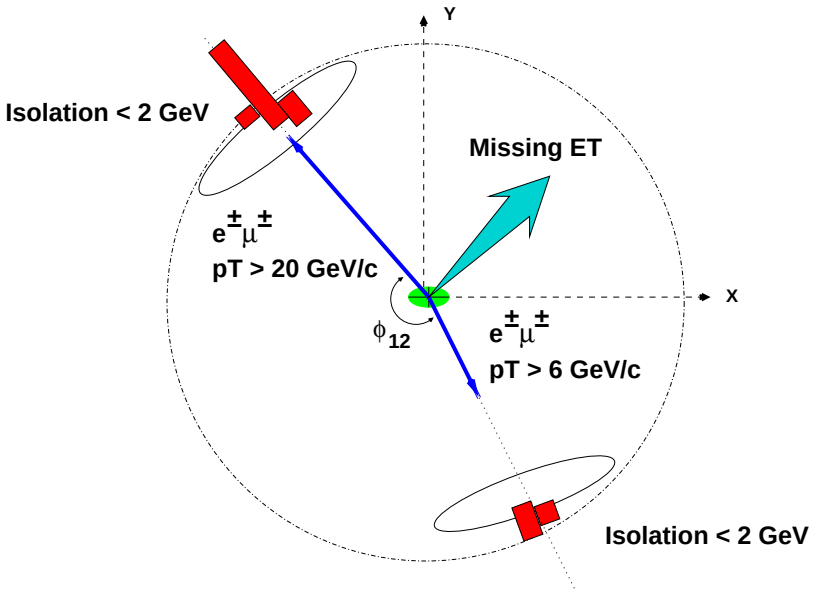
1. Like-Sign dilepton + $\not\!\!E_T$,
2. Very low background,
3. Fake or non-prompt lepton are main background.

Signal process:

1. High mass SM Higgs boson,
2. Bosophilic (or fermiophobic) Higgs as benchmark test

Search for the $WH \rightarrow WWW \rightarrow$ Like-Sign dilepton - contd

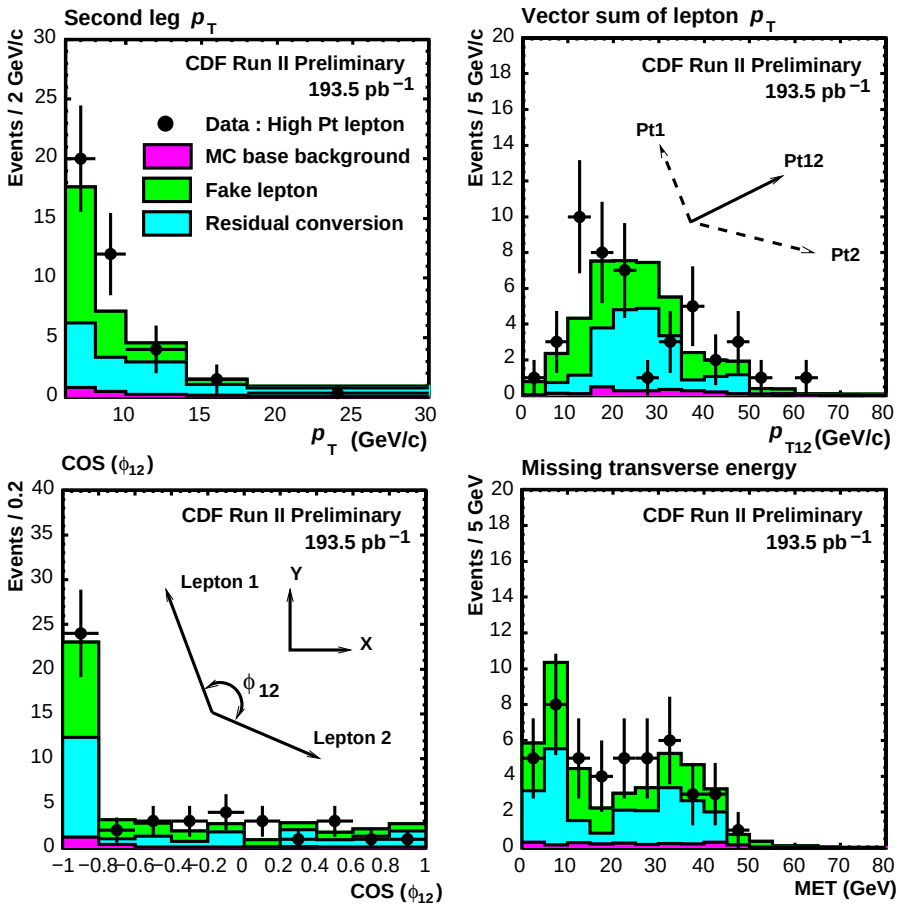
Event selection



Five combination

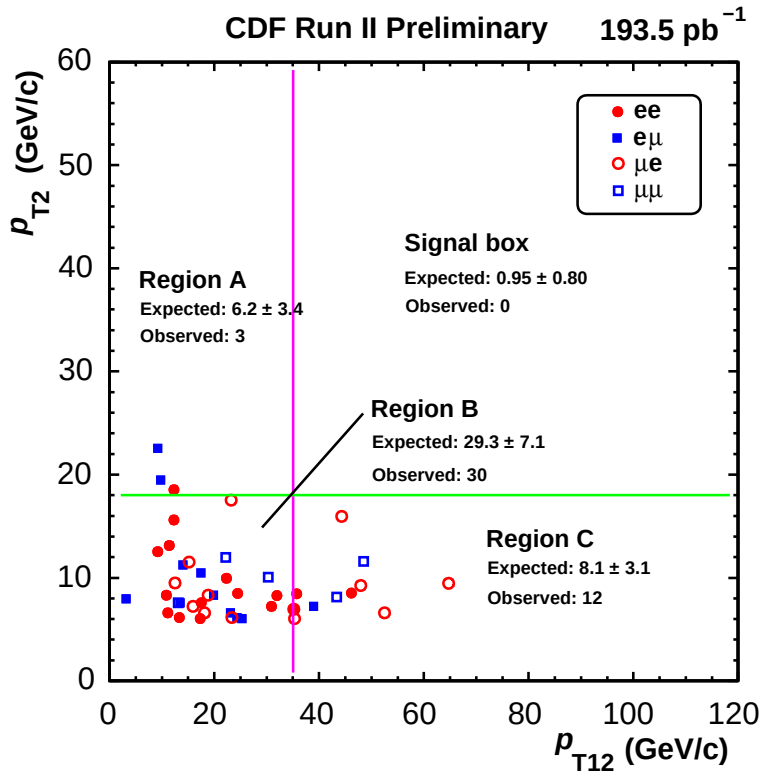
$e^{\pm}e^{\pm}$
$e^{\pm}\mu^{\pm}$
$\mu^{\pm}e^{\pm}$
$\mu^{\pm}\mu^{\pm}$
$l\,l\,l$

Expected and observed LS-dilepton event



Search for the $WH \rightarrow WWW \rightarrow$ Like-Sign dilepton - contd

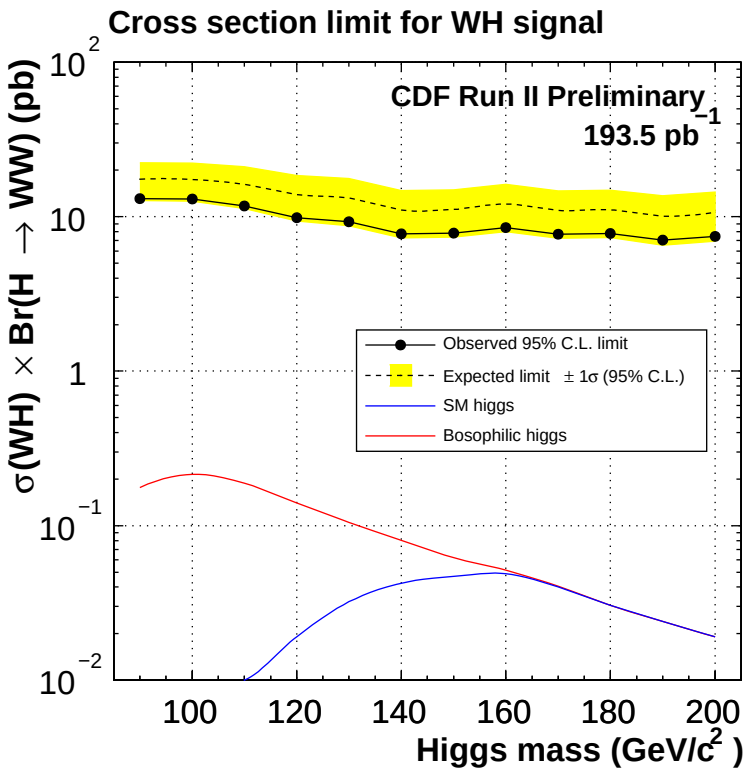
p_{T2} vs p_{T12} scatter plot



CDF Run II Preliminary (193.5 pb^{-1})

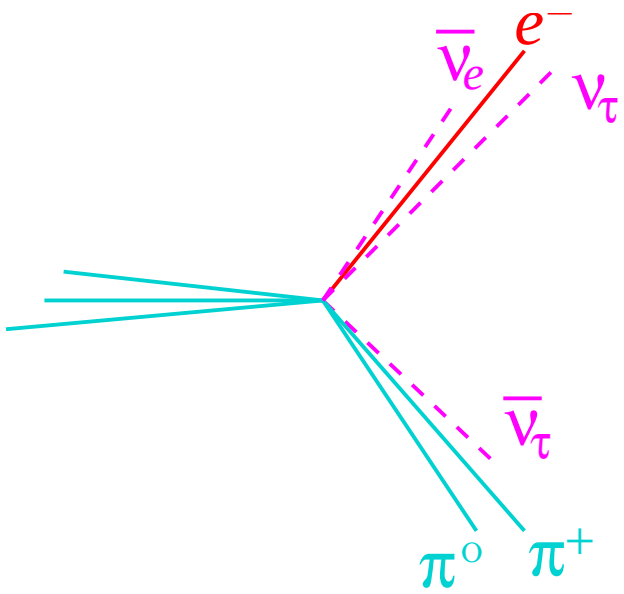
Region	Expected event	Observed event
A	6.2 ± 2.0(stat.) ± 1.4(sys.)	3
B	29.3 ± 3.8(stat.) ± 3.3(sys.)	30
C	8.1 ± 2.1(stat.) ± 1.0(sys.)	12
Signal box	0.95 ± 0.61(stat.) ± 0.18(sys.)	0

WH production limit at 95 % C.L.

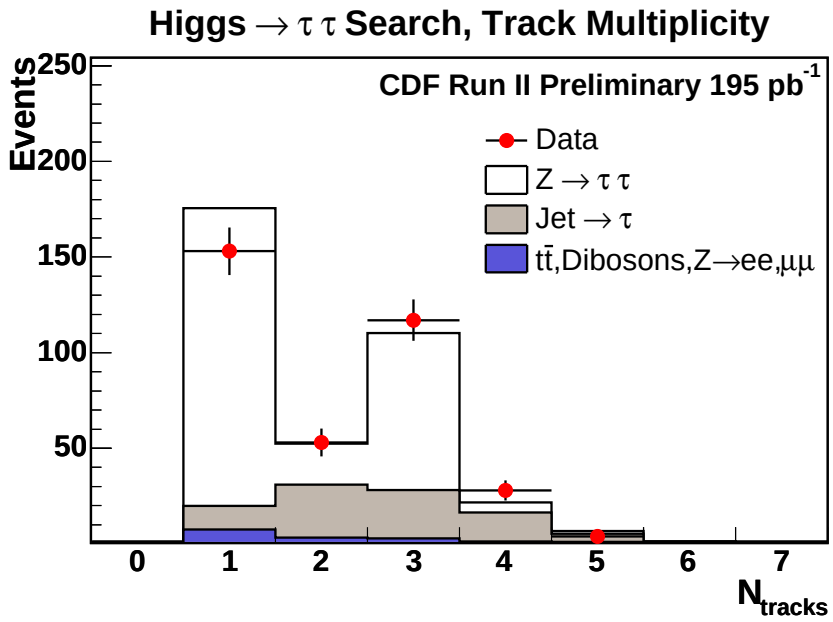


- $\sigma(WH) \times Br(H \rightarrow WW) <$ **12 pb at 110 GeV/c^2,**
- $\sigma(WH) \times Br(H \rightarrow WW) <$ **8 pb at 160 GeV/c^2.**

Search for the MSSM $h/A/H \to \tau^-\tau^+$



$h / A / H \to \tau^-\tau^+$



MSSM Higgs $\to \tau\tau$ Search, final events

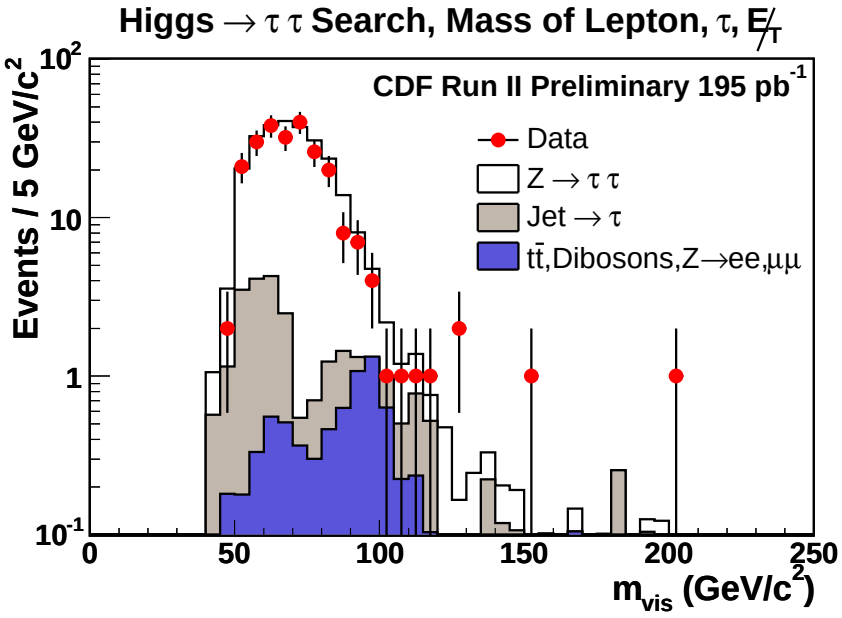
Signature

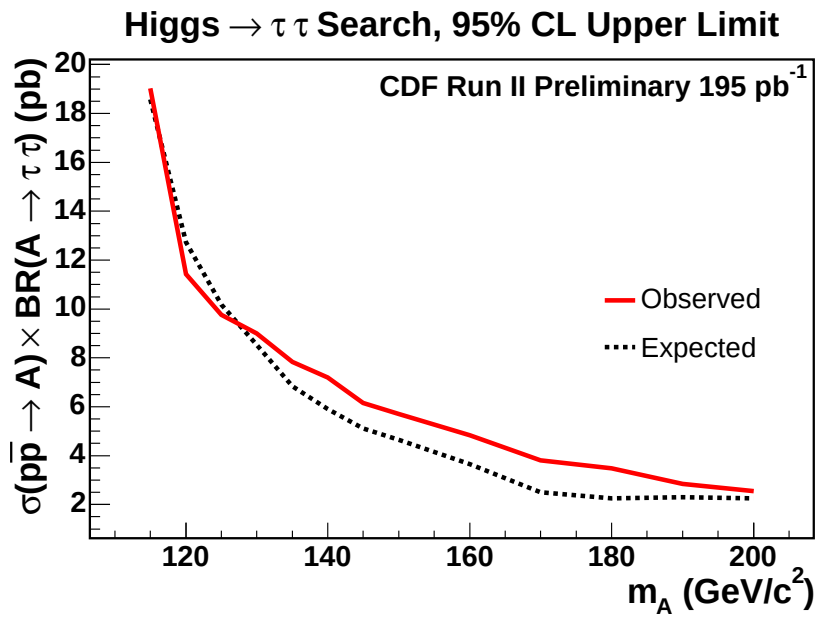
- **Semileptonic τ decay + Hadronic τ decay,**
- **$H_T >$ 50 GeV,**
- **Missing E_T should not point in opposite direction to τ decay products.**

	$\tau_h\tau_e$	$\tau_h\tau_\mu$	Combined
$Z \to \tau\tau$	132.3 ± 17.1	104.1 ± 13.3	236.4 ± 29.5
$Z \to ll$	1.8 ± 0.2	4.9 ± 0.4	6.7 ± 0.6
$t\bar{t}, VV$	0.7 ± 0.1	0.8 ± 0.1	1.5 ± 0.1
$jet \to \tau$	12.0 ± 3.6	7.0 ± 2.1	19.0 ± 5.7
Total predicted	146.8 ± 17.5	116.8 ± 13.5	263.6 ± 30.1
Data	133	103	236

CDF Run II Preliminary

Search for the MSSM $h/A/H \to \tau^-\tau^+$ - contd

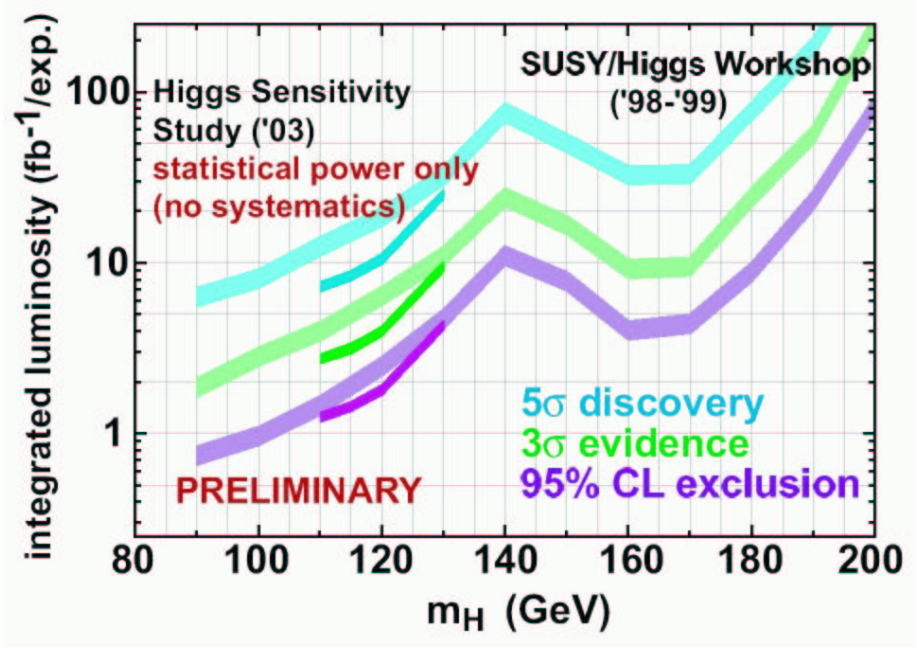




Result

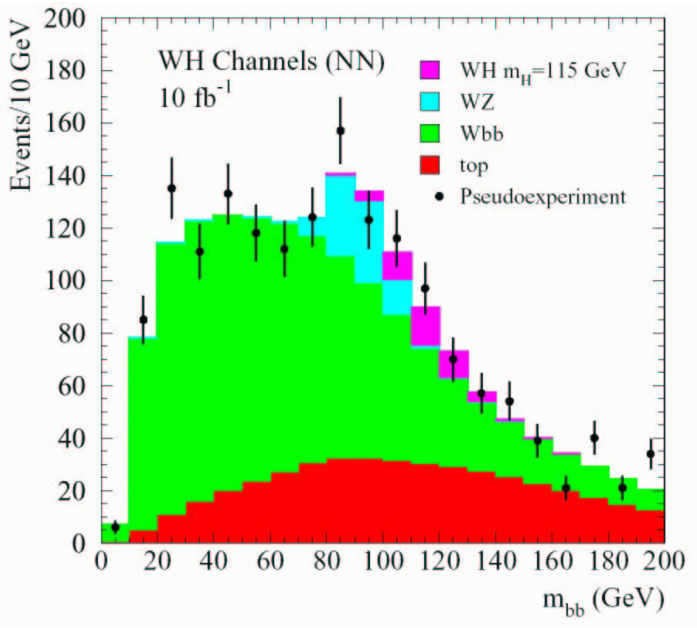
- Mass resolution worse at higher masses,
- Use binned likelihood fit to mass spectrum set 95 C.L. limit,
- Limit is order of magnitude higher than prediction($tan\beta$).

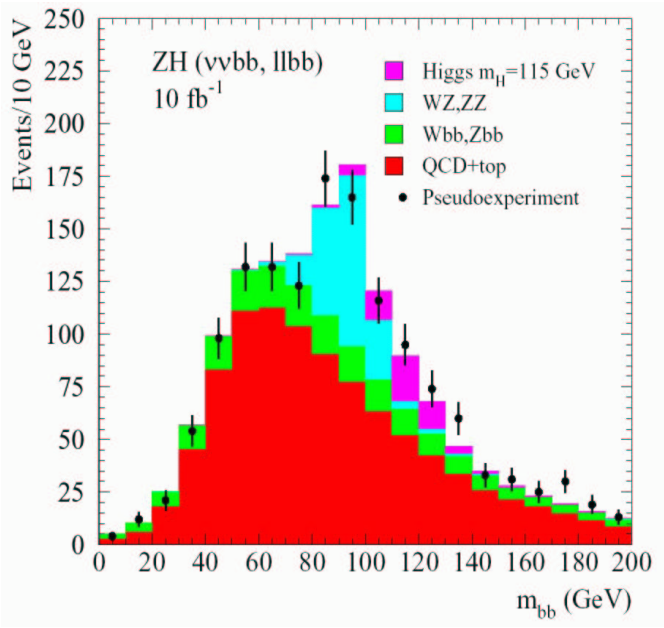
Re-evaluating Higgs Sensitivity at CDF



- CDF/DØ were asked by DOE to provide a new estimation of the Higgs Sensitivity based on current Run II detector performances (2003),
- Focus on the improvement of detector and analysis techniques (b-tag efficiency, dijet mass resolution, advanced analysis techniques),
- Finding consistent with SUSY-Higgs Workshop report (1998).

A Pseudo Experiment with Signal (115) and backgrounds





- Fit the dijet mass with signal and background,
- Extract the int. luminosity needed for the 95% C.L. exclusion limit, and 3 σ and 5 σ discovery.

Summary

- The Higgs boson remains elusive, but discovery may be just around the corner!
- The Tevatron is at the world's energy frontier until the LHC era,
- Already with 200 pb^{-1}, CDF and DØ have produced many interesting results,
- There is an extremely rich, exciting physics program ahead of us, every times we double the integrated luminosity we open a new window for new physics,
- The Higgs sensitivity will improve over time as we get more data, better understood detector, and getting smarter, but challenging ...
- With 5 fb^{-1} data, Tevatron will:
  - Exclude SM or SM-like Higgs mass up to 130 GeV/c^2 at 95% C.L.
  - Have a 3 σ discovery for Higgs mass up to 120 GeV/c^2,
  - Set a stringent limit on MSSM or more exotic Higgs in the parameter space beyond the SM
- Stay tuned!!