Higgs Searches at the Tevatron (Run I)

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on behalf of
CDF and DØ collaboration

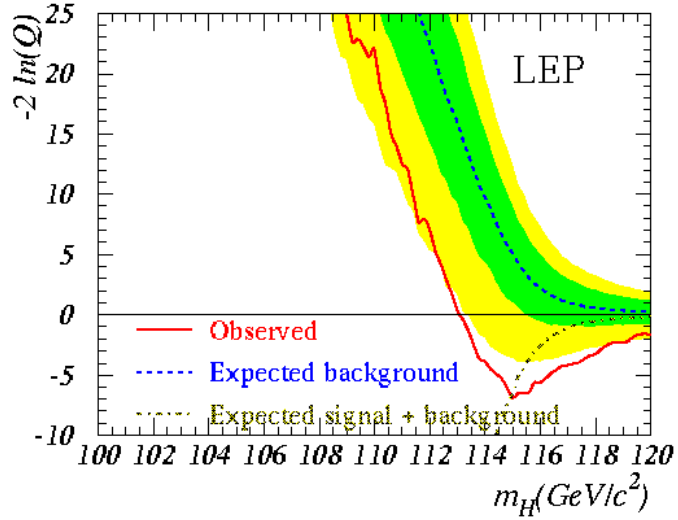
- Introduction
- SM Higgs
  - ZH & WH with $H \to b\bar{b}$ (CDF & DØ)
- MSSM Higgs
  - $b\bar{b}\phi$ with $\phi = H^0, h^0, A^0$ (CDF)
  - H^+ (CDF & DØ)
- Fermiophobic Higgs
  - $H \to \gamma\gamma$ (CDF & DØ)
- Conclusions

Introduction

- Electroweak Symmetry breaking in the SM predicts existence of an Higgs boson but with unspecified mass
  - Higgs mass constraints scale Λ where SM might break down
    - if $\Lambda = M_{Plank}$ then $130 < M(H) < 180$

Current Status of Higgs searches

- SM fit to Electroweak data indicates a light Higgs
  - $M(H) < \sim 200$ GeV @ 95 % CL
- Direct searches from LEP2
  - 95 % CL limit is ~ 113 GeV
  - Indication of Higgs-like events in the last year data:
    excess ~ 3σ at $M(H) \approx 115$ GeV

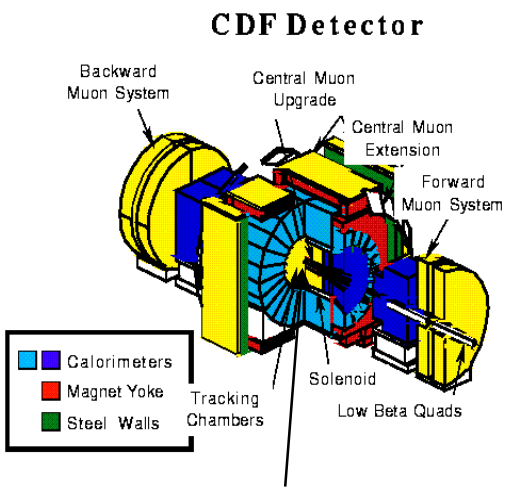


Tevatron (Run I)

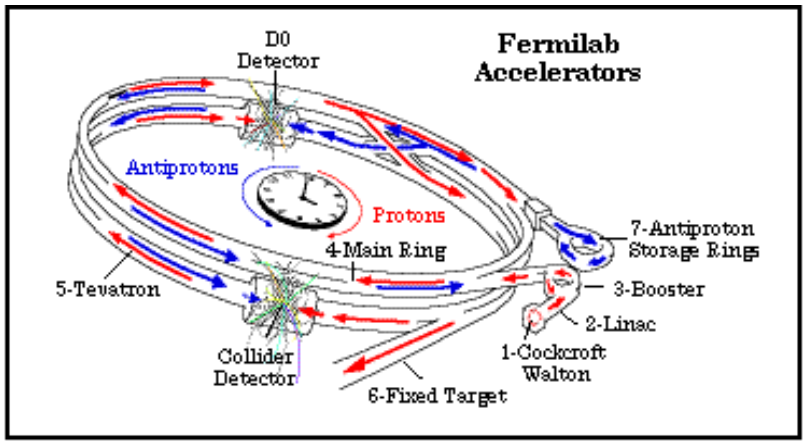
Tevatron

proton-antiproton collision @ $\sqrt{s}$ = 1.8 TeV

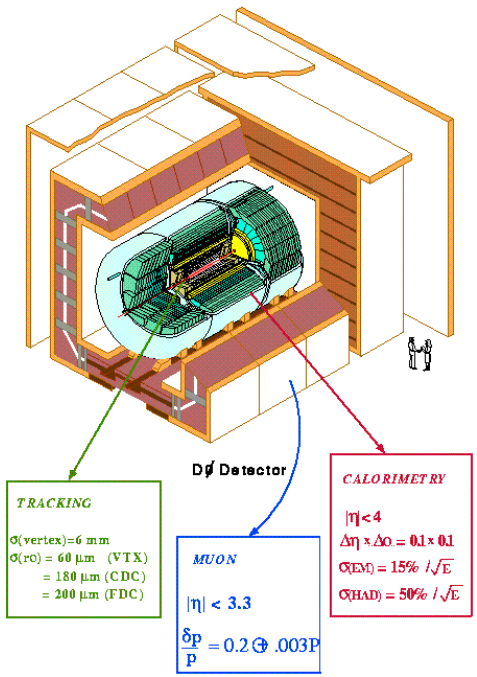
CDF



Silicon Vertex Detector



DØ



Run I (Oct. 92 → Feb. 96)

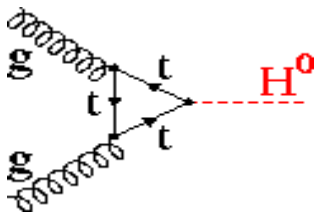
total integrated luminosity

~ 120^{-1} pb / detector

Expected ~ 2 fb^{-1} in Run IIa !

SM H^0 production @ Tevatron

- Gluon Fusion $gg \rightarrow H^0$

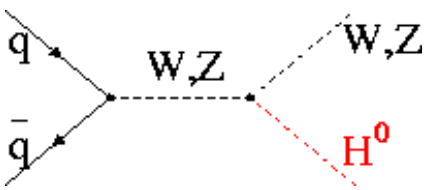


$\sigma = 0.70$ pb

for M(H) = 120 Gev/c^2
with QCD NLO correction

  - too difficult (QCD background)

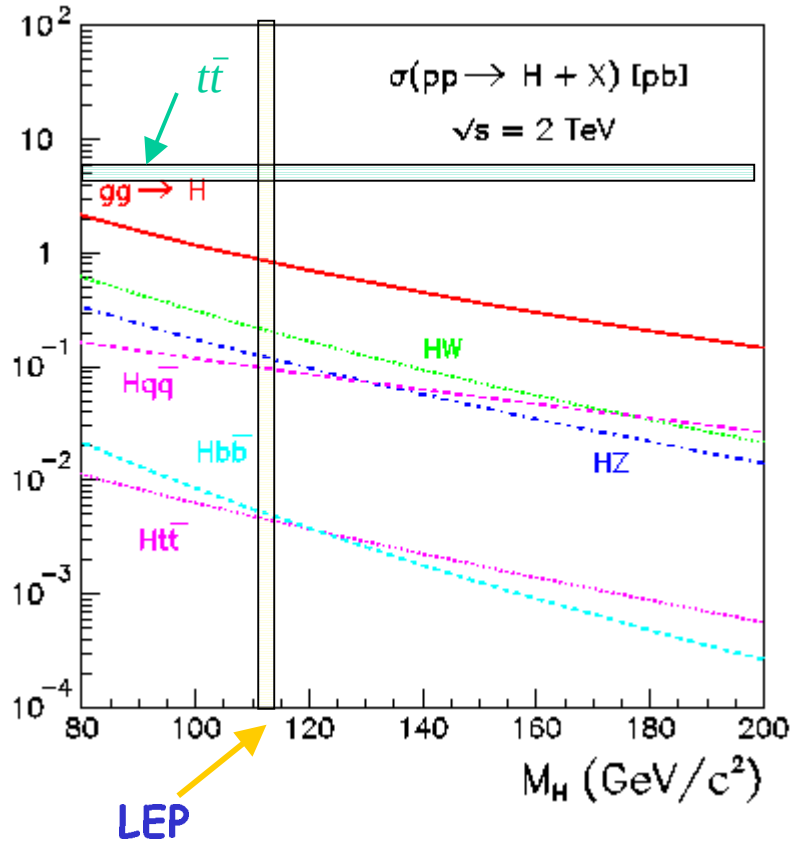
- Higgsstrahlung $q\bar{q} \rightarrow VH^0$



WH: $\sigma = 0.16$ pb

ZH: $\sigma = 0.10$ pb

  - SM cross section is very small
    - 1/20 σ(t-tbar)
    - 1/500 σ(Z/W + ≥ 2 jets)
  - possible with Run II luminosity !
  - larger σ with new physics ??



- Vector Boson fusion $q\bar{q} \rightarrow q\bar{q}H^0$
- radiation off heavy quark $q\bar{q} \rightarrow t\bar{t}H^0$
  - very small σ in the SM

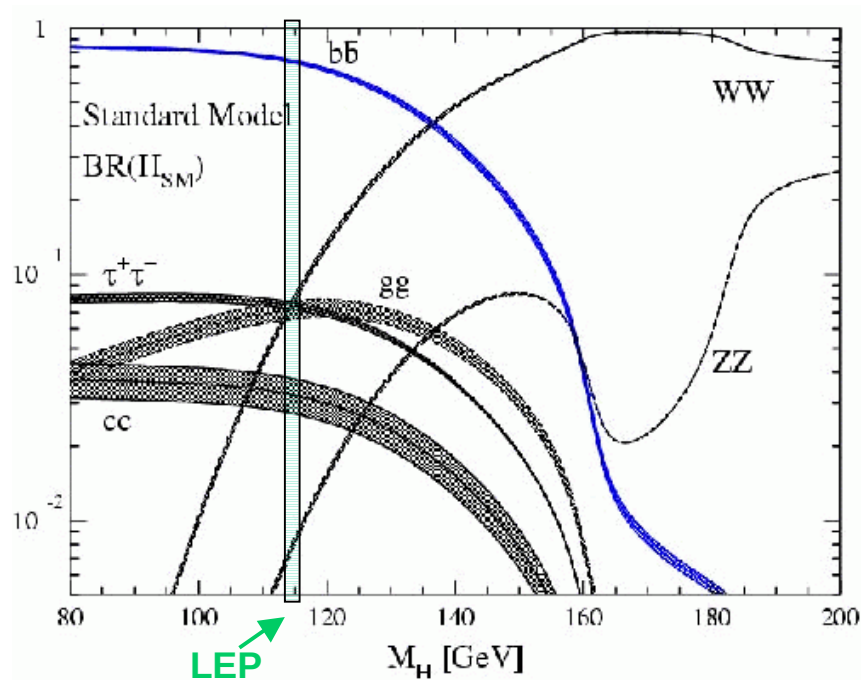
SM Higgs decays

- M(H) < 130 GeV
  - dominant decay is $H \to b\bar{b}$
  - final states are for W/ZH

    $q\bar{q}b\bar{b},\ \ell\nu b\bar{b},\ \nu\bar{\nu}b\bar{b},\ \ell^+\ell^- b\bar{b}$
  - need lepton ID/MET + b-tags
- M(H) > 130 GeV
  - dominant decay is $H \to W^+W^-$
  - final state with ≥ 2 leptons

    $gg \to H \to WW^* \to \ell^+\ell^-\nu\bar{\nu}$

    $VH \to WWW^* / ZWW^* \to \ell^\pm\ell^\pm jj$
  - but smaller cross-section
    - interesting at RunII !



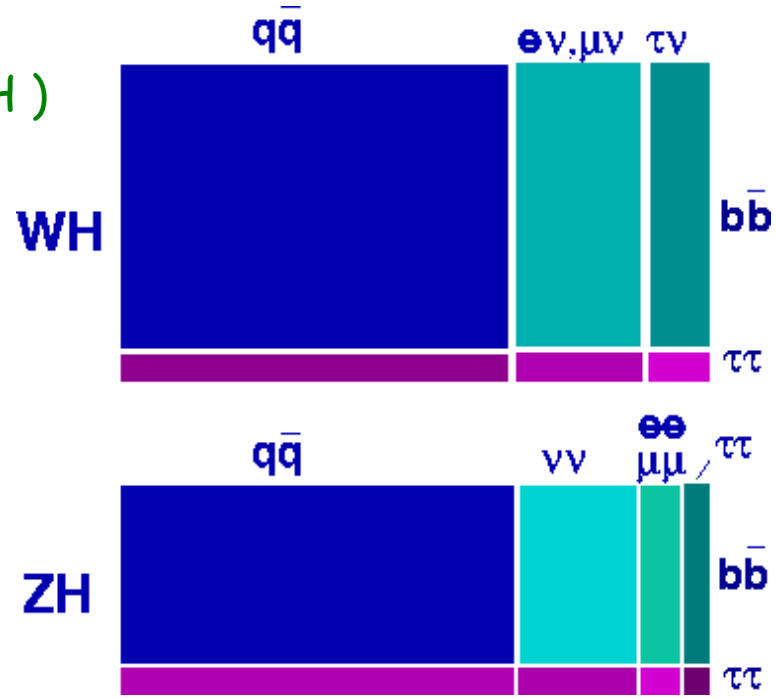
For M(H) = 120 GeV/c²

$$BR(H \to b\bar{b}) \approx 70\%$$
$$BR(H \to \tau^+\tau^-) \approx 7\%$$

SM H signatures (W /Z + H)

Tevatron Run I channels : (W/Z + H with M(H) < 130 GeV)

- $q\bar{q} + b\bar{b}$ (50% of W/Z H)
  - BG: QCD multijets
- $\ell\nu + b\bar{b}$ (9%)
  - BG: $Wb\bar{b}, t\bar{t}, WZ, t\bar{b}, tbq$
- $\nu\bar{\nu} + b\bar{b}$ (5.4%)
  - BG: QCD, $Zb\bar{b}, t\bar{t}, ZZ, t\bar{b}$
- $\ell^+\ell^- + b\bar{b}$ (1.8%)
  - BG: $Zb\bar{b}, t\bar{t}, ZZ, t\bar{b}$



Essential for these analyses:
- b tagging
- good di-jet mass resolution

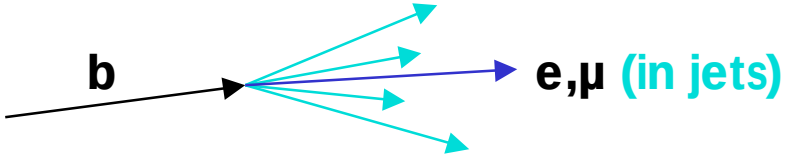
b tagging at the Tevatron

Techniques developed for top analyses. Two algorithms:

- Soft Lepton Tagging (SLT) (CDF & DØ)
  - semileptonic b decays:

$$b \to \ell \nu X \quad (\ell = e, \mu) \quad BR \approx 20\%$$

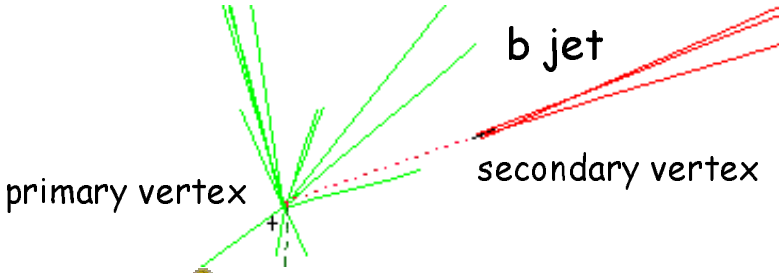
$$b \to c \to \ell \nu X \quad (\ell = e, \mu) \quad BR \approx 20\%$$



  - DØ: μ (p_T > 4 GeV) CDF: μ & e (p_T > 2 GeV)

ε(b-tag) ~ 7%/b-jet
ε(mistag) ~ 0.5%/jet

- Secondary Vertex Tagging (SVX) (CDF)
  - reconstruct a displaced vertex in the jet
  - b lifetime ~ 1.5 ps ➔ decay length ~ few mm
  - use capability of Silicon vertex detectors σ(decay-length) ~ 100 μm

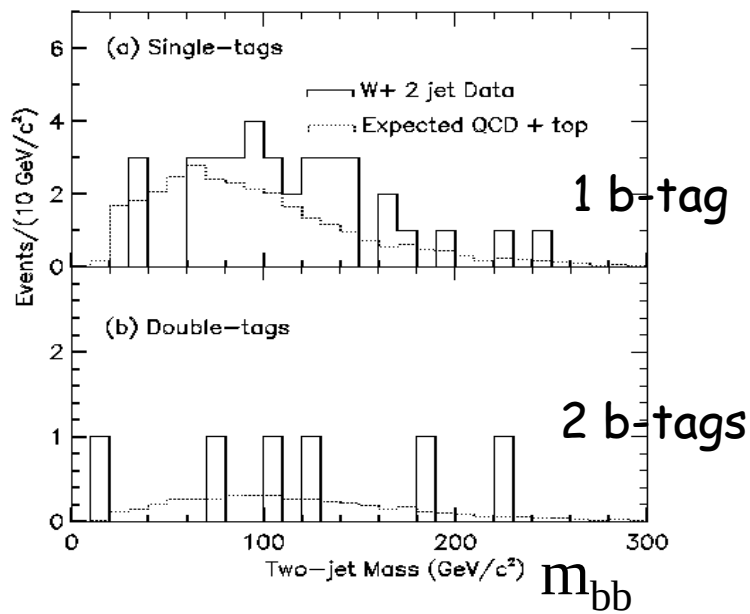


ε(b-tag) ~ 20%/b-jet
ε(mistag) ~ 0.2%/jet

Search for $WH^0 \rightarrow \ell\nu + b\bar{b}$

- Final states are lepton (e/μ) + MET + b's
- Event selection:
  - high $p_T$lepton: p_T(lep) > 20 GeV & η<1
  - MET>20
  - 2 jets with E_T(j)>15, η<2
  - b-tags (single OR double jet tag)
- Backgrounds:
  - $Wb\bar{b}, t\bar{t}, WZ, t\bar{b}, tbq$

CDF



Results (CDF & DØ) 106 pb^{-1}

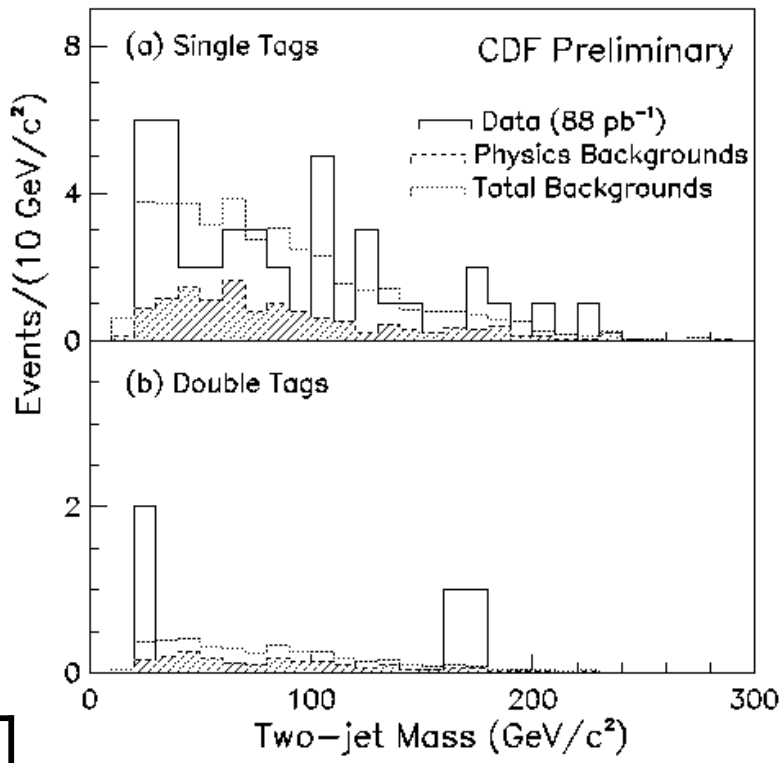
Exp.	channel	backg	data	Br x accept. (90<m(H)<130)
CDF	1 b-tag	30 ± 5	36	~ 0.6 - 0.8 %
CDF	2 b-tags	3 ± 1	6	~ 0.2 - 0.3 %
DØ	1 b-tag	25 ± 3	27	~ 0.6 - 0.9 %

from fit to di-jets mass:

95% CL Limit on σ×BR:
26-28 pb for 90<M_H<130 (CDF)
40-19 pb for 90<M_H<120 (DØ)

Search for $ZH^0 \rightarrow \nu\bar{\nu} + b\bar{b}$

- Final states is MET + b's
- Event selection (CDF):
  - MET>40 (trigger >35) + lepton veto
  - 2 or 3 jets with $E_T(j)>15$, $\eta<2$
  - $\Delta\Phi(MET,j) > 60°$ for all jets ($E_T>8$)
  - $\Delta\Phi(j_1,j_2) < 150°$
  - b-tags (single OR double)
- Backgrounds:
  - QCD and $Zb\bar{b}, t\bar{t}, ZZ, t\bar{b}$



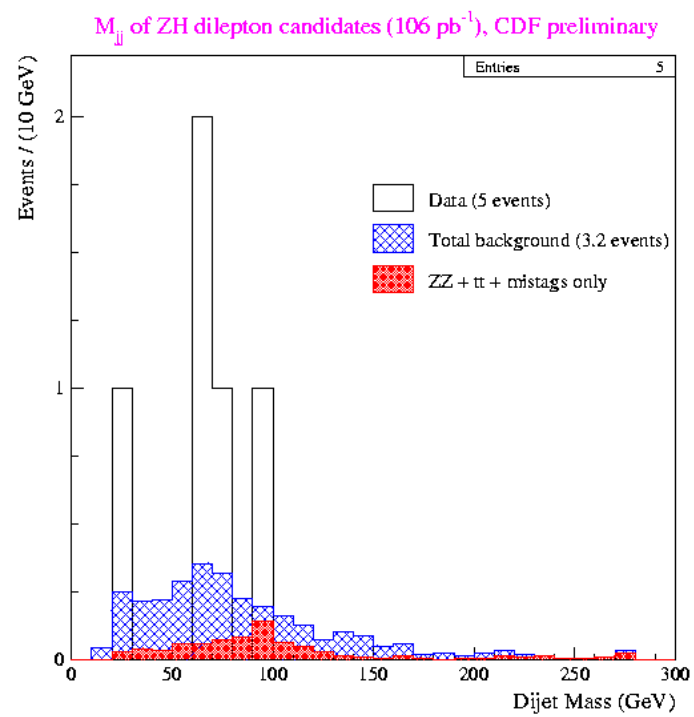
Results (88 pb^{-1})

Exp.	channel	backg	data	Br x accept. (90<m(H)<130)
CDF	1 b-tag	39 ± 4	40	~ 0.5 - 0.8 %
CDF	2 b-tags	4 ± 1	4	~ 0.4 - 0.5 %

95% CL Limit on $\sigma \times BR$:
~ 8 pb for $90<M_H<130$

Search for $ZH^0 \rightarrow \ell^+\ell^- + b\bar{b}$

- Final states is di-leptons + b's
- Event selection (CDF):
  - p_T(lep)>20,10 GeV
  - 76<M(l,l)<106 GeV
  - 2 or 3 jets with E_T(j)>15, η<2
  - MET < 50 GeV (against top di-lepton evts)
  - 1 b-tag
- Backgrounds:
  - $Zb\bar{b},\ Zq\bar{q},\ t\bar{t},\ ZZ,\ t\bar{b}$



m_{bb}

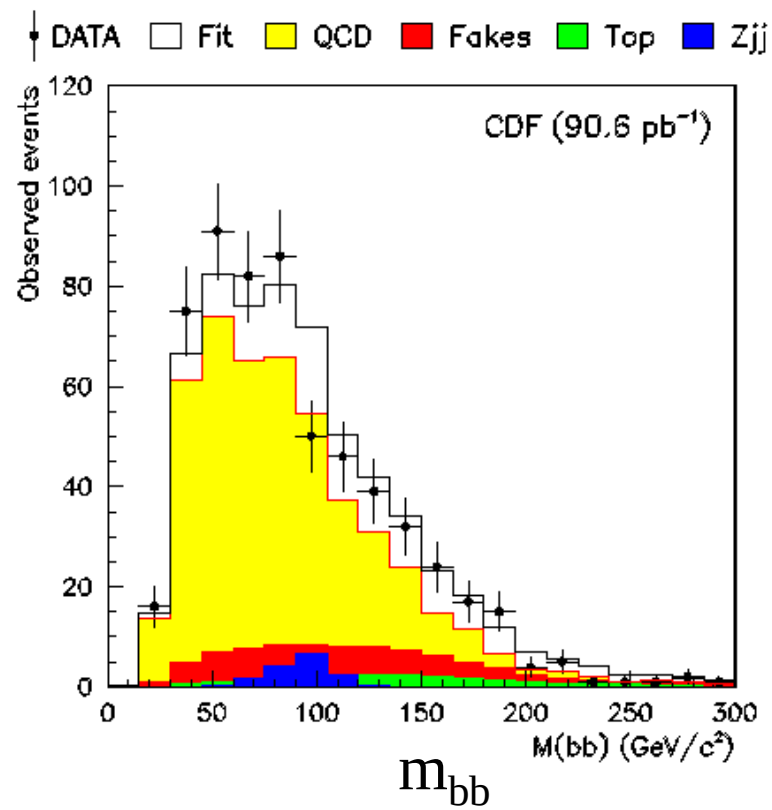
Results (106 pb^{-1})

Exp.	channel	backg	data	Br x accept. (90<m(H)<130)
CDF	1 b-tag	3 ± 1	5	~ 0.2 %

95% CL Limit on $\sigma\times$BR:
56-24 pb for 90<M_H<130

Search for $W/Z + H^0 \rightarrow q\bar{q} + b\bar{b}$

- Multi-jet final state with b's
- Event selection (CDF):
  - Multi-jets trigger
    - $\geq$ 4 jets with ΣE_T>125 GeV & E_T>15
  - double b-tag
  - $p_T(b\bar{b})$>50 GeV
- Backgrounds:
  - mainly QCD (b's + fakes)
  - also top and Z + jets



Results (91 pb^{-1})

Exp.	channel	back.	data	Br x accept. (90<m(H)<130)
CDF	2 b-tag	~ 600	589	~ 1.5 - 2.9 %

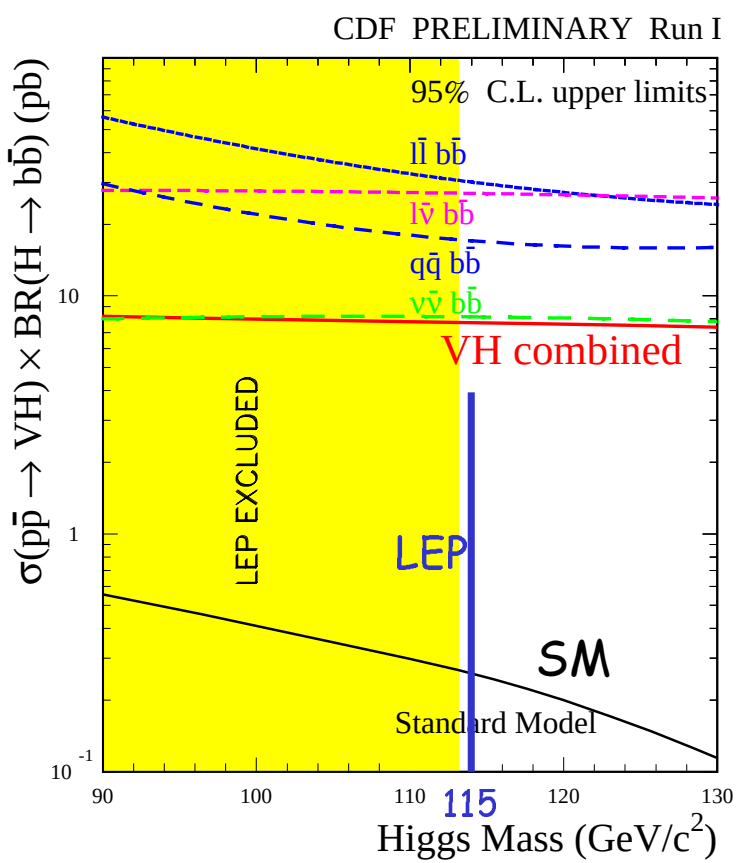
95% CL Limit on $\sigma \times$BR:
30-16 pb for 90<M_H<130

➔ Need good M_{bb} resolution against background

Combined limit for SM Higgs

CDF combination of $q\bar{q}b\bar{b},\ \ell\nu b\bar{b},\ \nu\bar{\nu}b\bar{b},\ \ell^+\ell^- b\bar{b}$

95 % CL limit on $\sigma(p\bar{p} \to WH, ZH) \times BR(H^0 \to b\bar{b})$



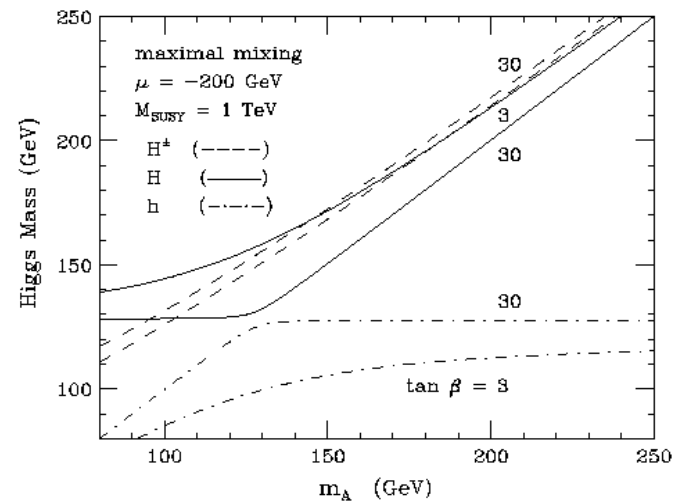
σ_{limit} = 7.4-8.2 pb
for m_H = 90-130 GeV/c^2

- x 30 SM cross-section (m_H = 115)
- Limit is dominated by $\nu\nu b\bar{b}$
- Expected best limits from:
  - $\nu\nu b\bar{b}$ and $l\nu b\bar{b}$
- poor $l\nu b\bar{b}$ limit due to a small excess in observed events
- Need more luminosity

RUN II

MSSM Higgs Search

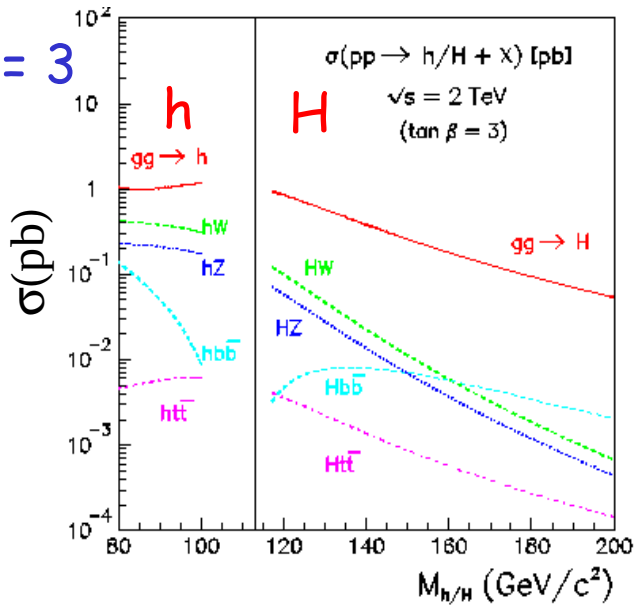
Two Higgs doublets in the MSSM



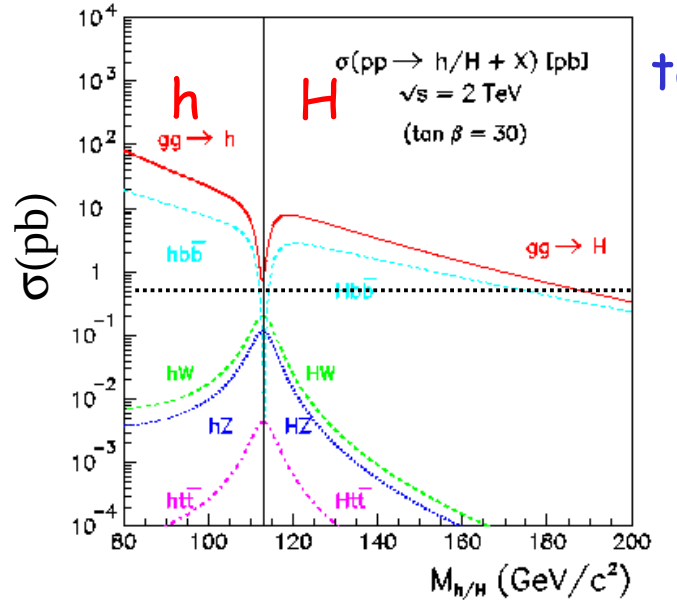
- 5 Higgs particles
  - two neutral CP-even: h^0,H^0
  - One neutral CP odd: A^0
  - Two charged: H^+,H^-
- two free parameters: $\tan\beta$ and m_A
- Mass relations at tree level:
  - $m(h^0) < m(Z^0) < m(H^0)$; $m(A^0) < m(H^0)$; $m(H^+) < m(W)$
  - but after radiative corrections $m(h^0) < \sim 130$ GeV
- Couplings at large $\tan\beta$:
  - enhanced to d-type quark and leptons
  - suppressed to u-type quark

MSSM Higgs production

tanβ = 3



tanβ = 30

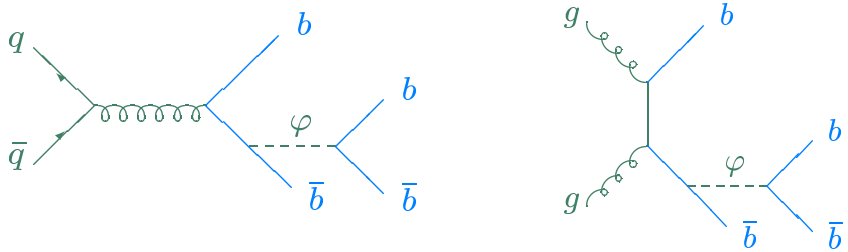


- Small tanβ :
  - SM-like cross-sections
- Large tanβ
  - enhanced $hb\bar{b}$ coupling
  - $hb\bar{b}/Hb\bar{b}/Ab\bar{b}$ can have large cross-sections ($\propto \tan^2\beta$)

In general dominant Higgs's Branching Ratio are to $b\bar{b}$ (90%) and $\tau^+\tau^-$ (10%)

Search for $p\bar{p} \to b\bar{b}\,\varphi \to b\bar{b}\,b\bar{b}$

- Exploit enhanced Yukawa couplings looking for $b\bar{b}\varphi$ production (φ = h,HA)
- large cross sections ($\propto \tan\beta^2$)
- 4-b's jets final state
- Event selection (CDF):
  - Multi-jets trigger
    - 4 jets with $\Sigma(E_T)$>125 GeV & E_T>15
  - ET(j) cuts depending on m(φ)
  - $\geq$ 3 b-tags
  - $\Delta\Phi(b\bar{b})$ > 109° (against $g \to bb$)



- Backgrounds:
  - QCD ($b\bar{b}$/cc), Z/Wjj, top

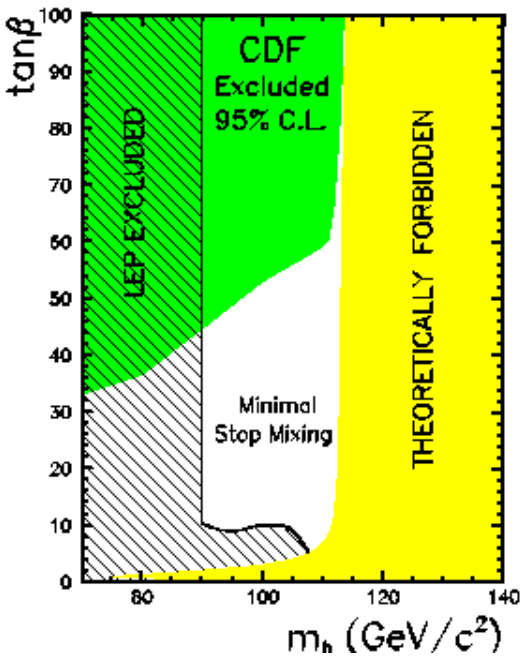
CDF results (91 pb^{-1})

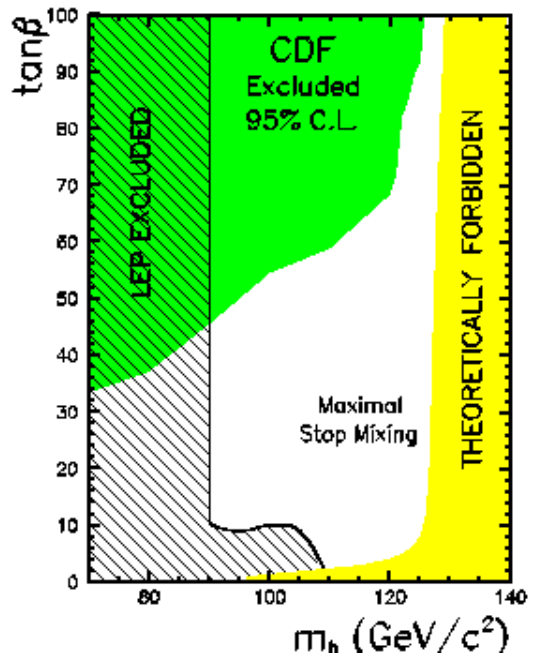
M(φ) (GeV)	BR x acc.	backg	data
70	0.16 %	4.6 ± 1.4	5
120	0.28 %	3.5 ± 1.1	2
300	0.59 %	0.1 ± 0.4	0

Limit for $p\bar{p} \to b\bar{b}(h/H/A) \to b\bar{b}b\bar{b}$

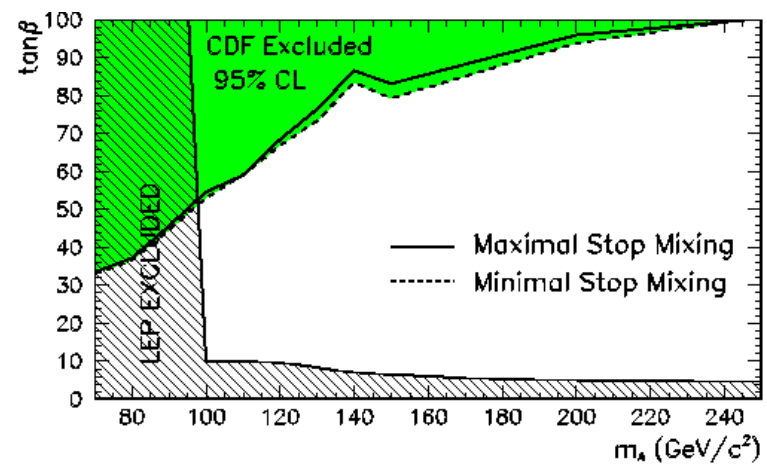
- Limit (95%CL for Mφ = 100 GeV): σ·BR < 25.7 pb
- convert σ·BR limit in tanβ vs Higgs mass exclusion
  - No mixing & Maximal Mixing for the stop

tanβ vs m(h)





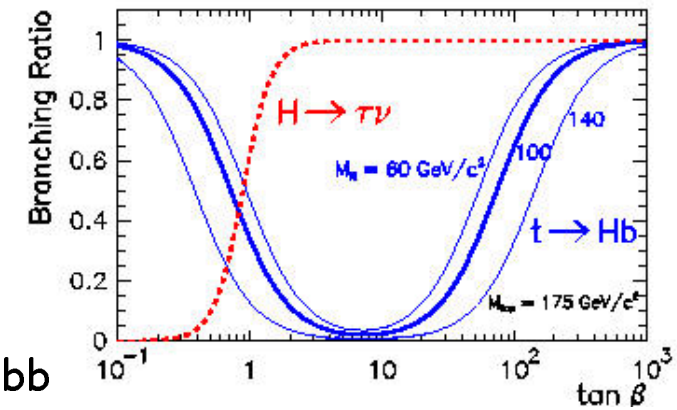
tanβ vs m(A)



Tevatron complements LEP !

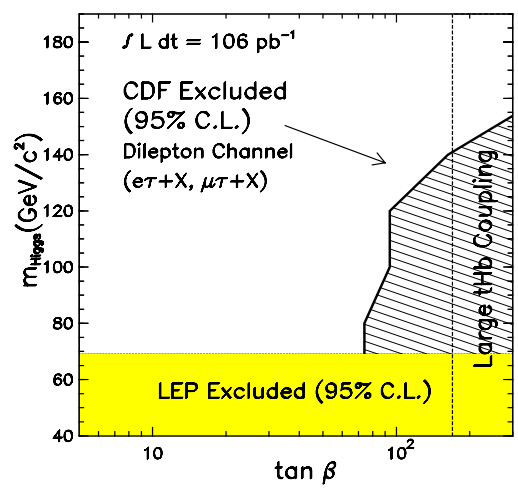
Charged Higgs Searches

- Searches for $t \to H^+b$ when $M(H^+) < m_t - m_b$
- decay $t \to H^+b$ can compete with SM decay $t \to W^+b$
- $BR(t \to H^+b)$ depends on $\tan\beta$



Direct Search (CDF):

- look for $H^+ \to \tau\nu$ in t-tbar evts
  - $BR(H^+ \to \tau\nu) \sim 1$ for large $\tan\beta$
  - WHbb or HHbb channels in addition to WWbb
  - look for $l + \tau + MET + jj$ events ($l = e,\mu,\tau$)
  - use τ identifications via hadronic decays (tracking + calorimeter)
  - backgrounds:
    - $Z \to \tau\tau + jj$, $W+\geq 3$ jets, WW/WZ
  - acceptances for single and double $H^\pm$ production

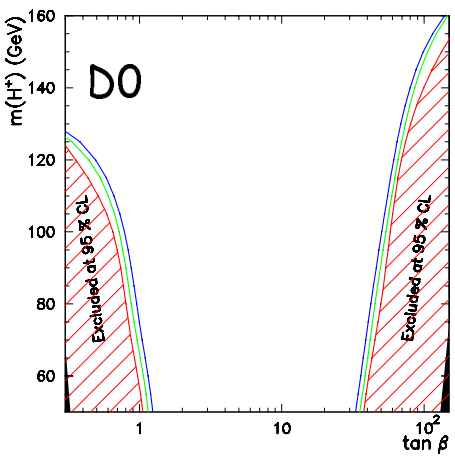


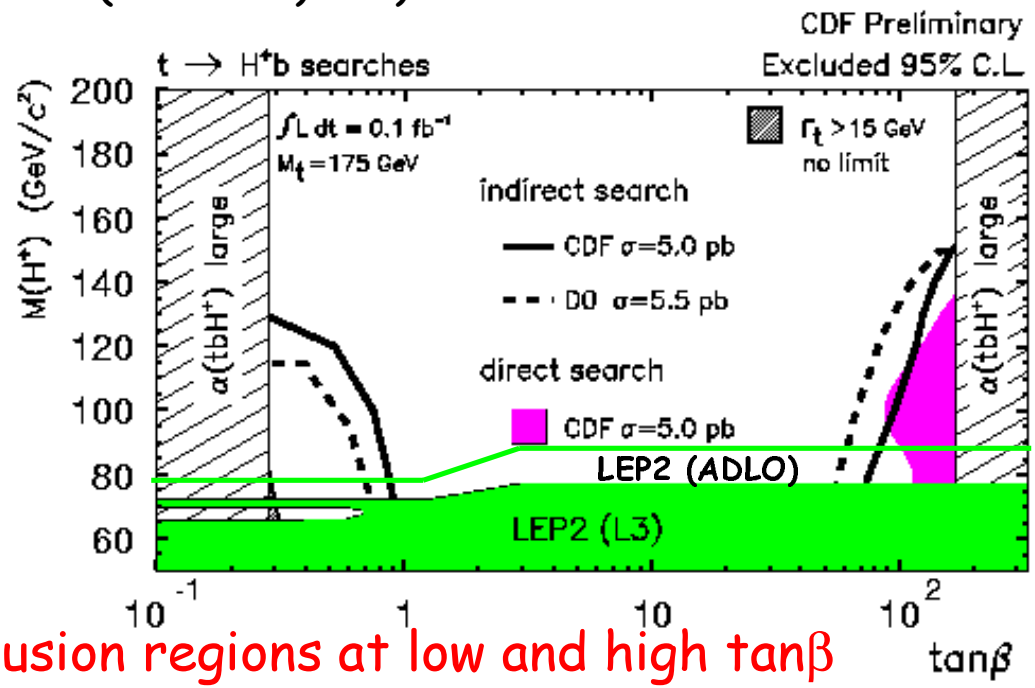
Charged Higgs Searches

Indirect Search (CDF + DØ)

- look for lepton disappearance in t-tbar events
  - suppression of dileptons and lepton + jets events
  - rate of the two depends on BR($t \to H^+b$)
  - t-tbar cross-section independent of m(H), tanβ
  - given measured x-section (when BR($t \to H^+b$) = 0)

exclusion regions in the m(H^+)-tanβ plane



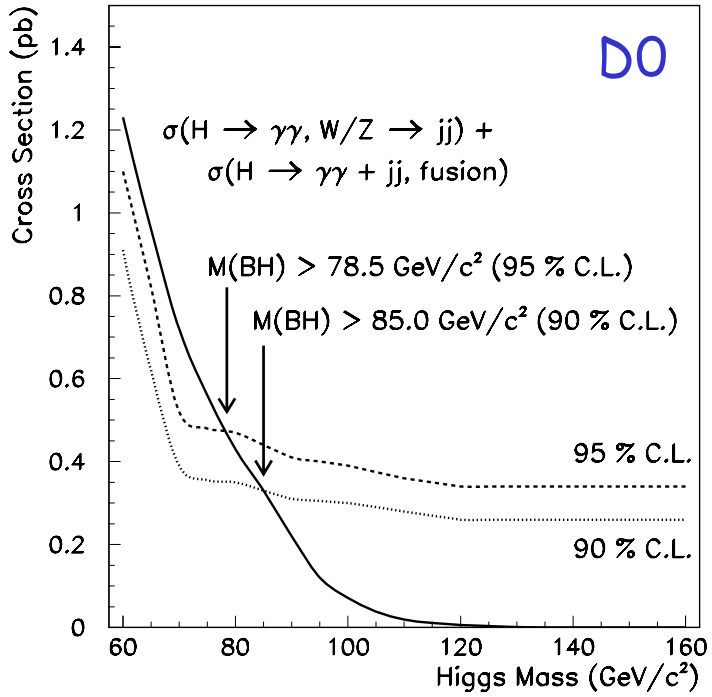


New Exclusion regions at low and high tanβ

Fermiophobic Higgs

- In some models Higgs couples only to vector bosons
- BR($H \rightarrow \gamma\gamma$) dominant for light Higgs (m(H) < 100)
- Searches for W/Z + $H \rightarrow \gamma\gamma jj$
  - DØ search:
    - di-photons + jets
    - Backgrounds from QCD
      - fakes or real γ in jets
  - CDF search
    - di-photons with e/μ + MET or jj
- Limit For SM cross-section:

  ➔ M(H) > ~ 80 GeV (95% CL)
- LEP limit is ~ 105 GeV



Conclusions

- SM Higgs searches are luminosity limited in Run I
  - no sensitivity to SM cross sections
  - no excess seen and set limits at ~30 SM cross-section
  - provided experience for Run II
  - developed techniques for low mass Higgs searches
    - b tagging and di-jet mass resolution are crucial !
  - good expectations for Run II
    - ➔ see next talk on Run II prospects

report of the Tevatron Higgs Working Group (hep-ph/0010338)

- Nice exclusion results for MSSM Higgs:
  - $bb\varphi$ search with sensitivity for high $\tan\beta$ region
  - charged Higgs from $t \rightarrow H^+b$
  - probed regions inaccessible to LEP
  - very interesting in Run II