Search for SM Higgs at the Tevatron

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For the CDF and DØ Collaborations

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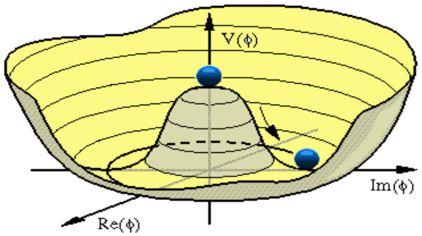
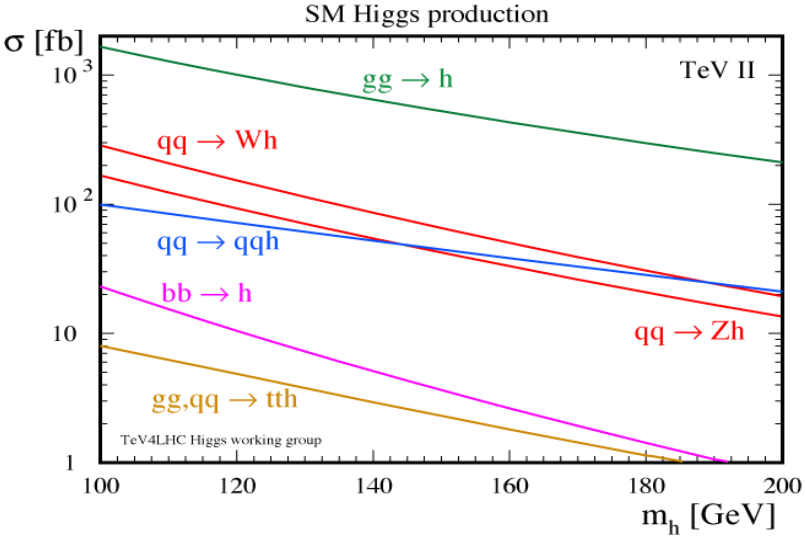
The SM Higgs

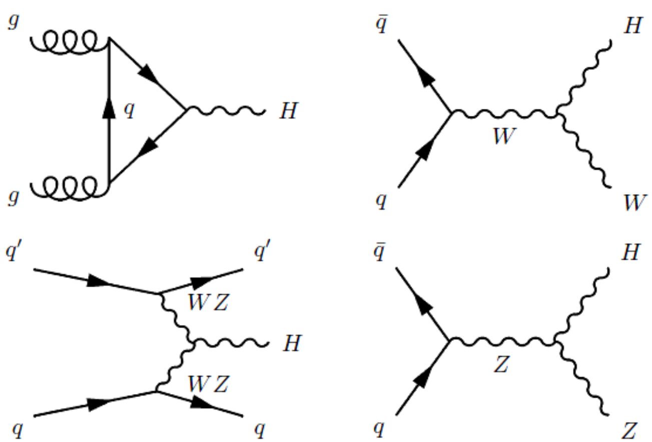
SM Higgs: massive scalar predicted by the Higgs mechanism of EW symmetry braking

- Higgs mass is a free parameter
- LEP direct search: m_H>114 GeV @ 95% CL
- Constraints from fits of EW data:
  - Best fit: $m_H = 90^{+36}_{-27}\,\mathrm{GeV};\, m_H < 163\,\mathrm{GeV}\,@\,95\%\,\mathrm{CL}$
- EW fit + LEP: m_H< 191 GeV @ 95% CL
  Clear indication that SM Higgs is fairly light **if** it exists



Dominant production mechanisms and decays





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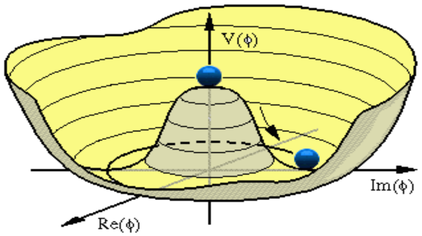

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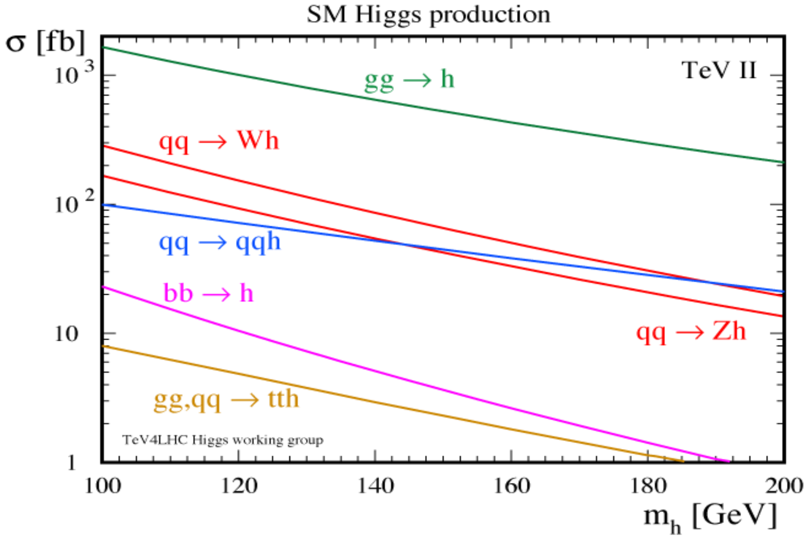
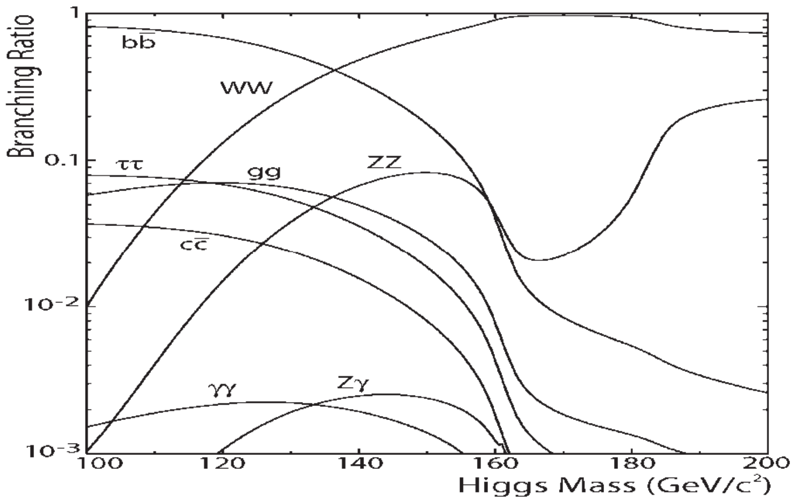
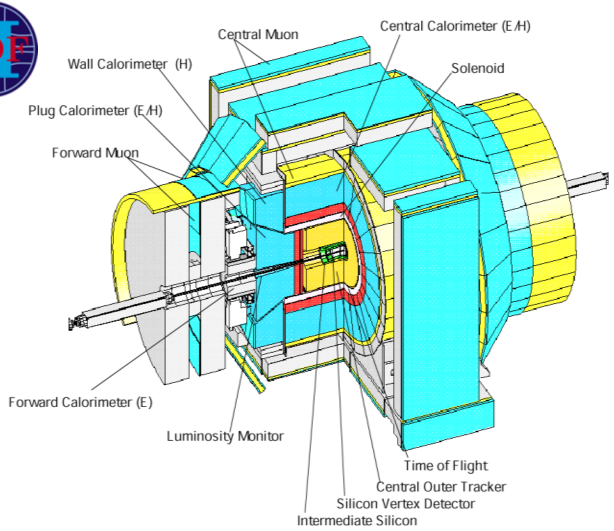
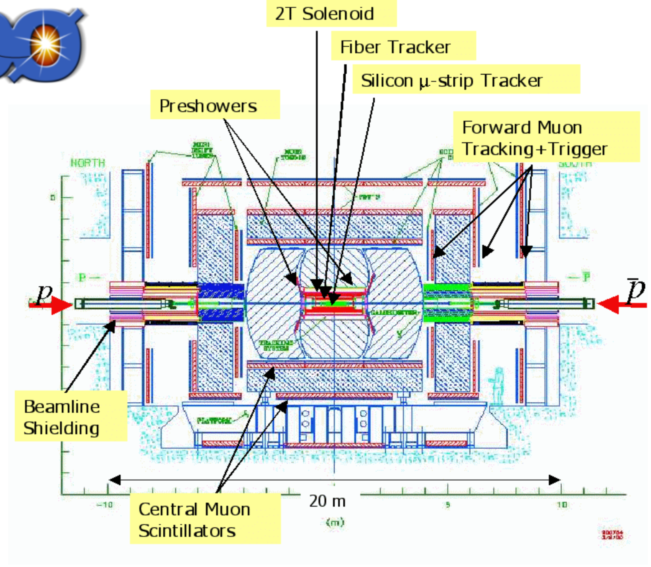




Experimental Environment





- The Fermilab Tevatron
  - $p\bar{p}$ collider with, E_{CM} = 1.96 TeV
  - Delivered over 6 fb^{-1} of data in Run 2

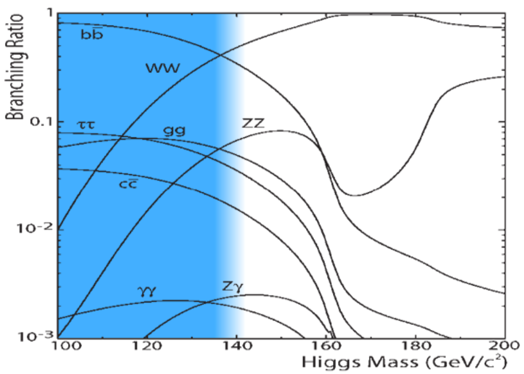
- CDF and DØ:
  - Build around two opposing pp interaction points
  - General-purpose, cylindrically symmetric detectors with calorimetry, tracking, muon systems
  - Well understood, stable operation over a long period of time
  - Accumulated over 5 fb^{-1} of quality data (per experiment) in Run 2

(Presented results use up to 4.2 fb^{-1} of data)

Strategy for the SM Higgs Search at the Tevatron

- Cover as many search channels as possible
  - Combine results of channels
  - Combine CDF and DØ results
- Extract maximum information through use of multivariate techniques
  - Artificial Neural Nets (NN)
  - Boosted Decision Trees (BDT)
  - Likelihoods using Matrix Element (ME) methods
  - Combinations of the above

Low-mass Higgs



- Dominant decay for m_H<135 GeV: $H \rightarrow b\bar{b}$
- Need efficient b-tagging algorithms:
  - Most CDF analyses use secondary vertex + jet probability taggers; DØ uses a NN

- Search in the main production mode ($gg \rightarrow H$) is not realistic due to large backgrounds; best strategy:
  - Look for associated production: H+W/Z
  - W/Z reconstructed in leptonic decay modes
- Perform searches in several topological final states
  - Most sensitive: MET+l+$b\bar{b}$, ll$b\bar{b}$, MET+$b\bar{b}$

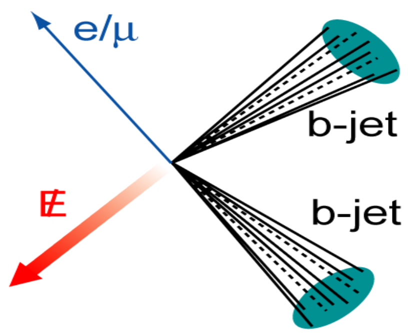
MET+l+$b\bar{b}$ Final State

Higgs signal:

- $WH \rightarrow l\nu b\bar{b}$

Major backgrounds:

W+jets, $t\bar{t}$, multi-jets

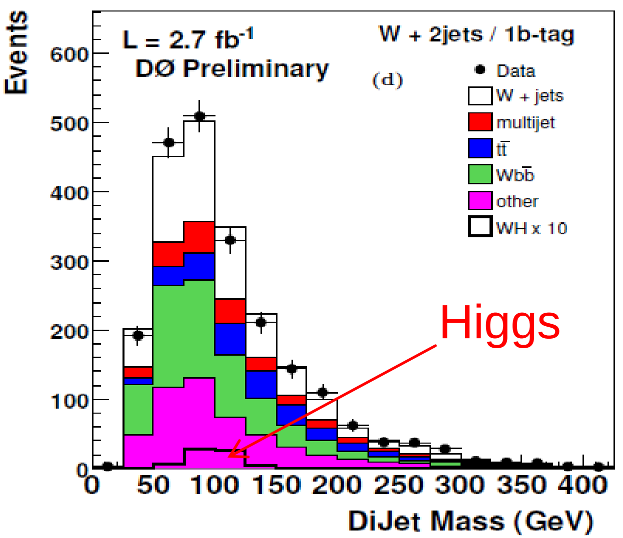


Selection

MET>20 GeV
One lepton: p_T>20 GeV (CDF)
p_T>15 GeV (D0)
Jets: N_{jet} = 2; E_T>20 GeV, $|\eta|$<2.0 (CDF);
N_{jet} = 2,3; E_T>20/25 GeV, $|\eta|$<2.5 (D0);
One or more b-tags

Di-jet mass (D0)

→ Use multivariate discriminators to Improve signal/bg separation



DØ: split sample into 4 categories according to number of jets and b-tags

Signal extraction: NN with kinematic variables and the ME discriminants

CDF: split into 3 categories according to b-tags

Signal extraction:

1. NN with kinematic variable
2. BDT: kinematics, ME, flavor separating NN

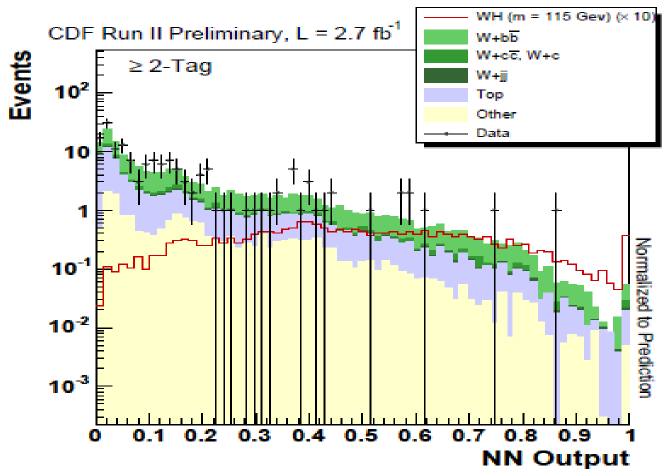
Combined NN 'superdiscriminant'

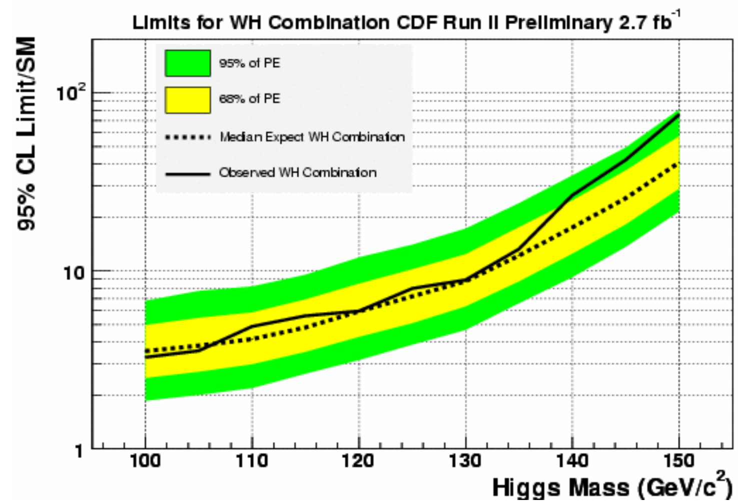
MET+l+b$\bar{b}$ Final State: Limits

Example output distributions obtained for subsamples

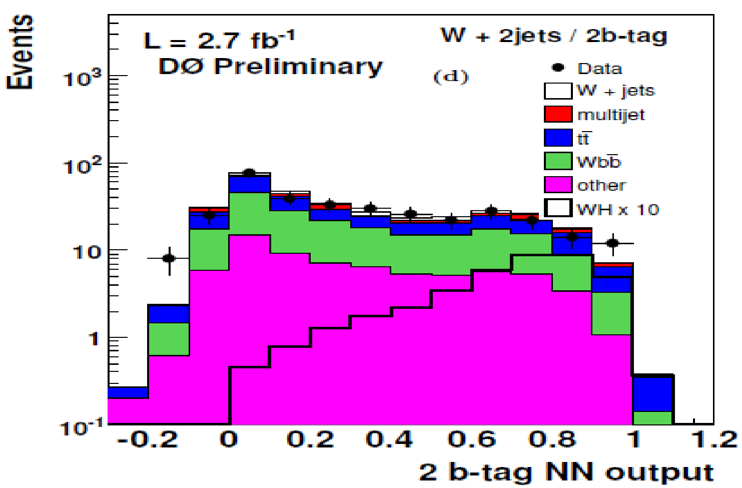
2.7 fb^{-1}

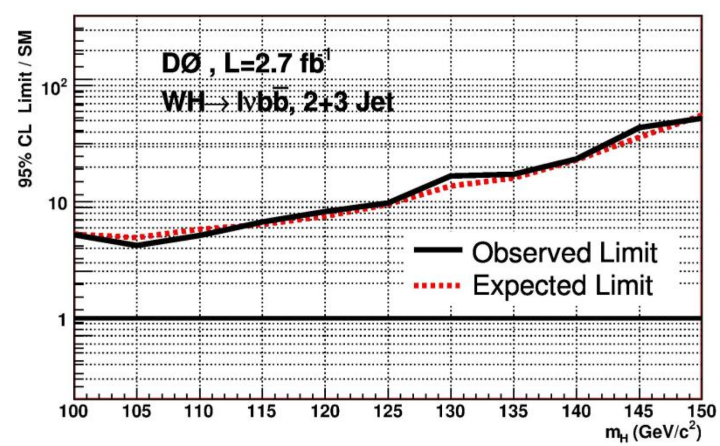
Expected and observed limits





m_H=115 GeV
Obs: 5.6 x σ_{SM}
Exp: 4.8 x σ_{SM}

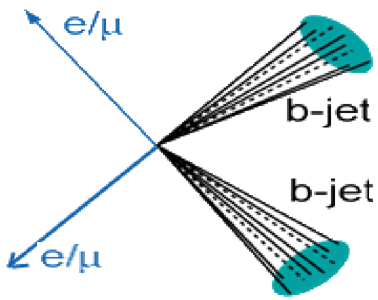




m_H=115 GeV
Obs: 6.7 x σ_{SM}
Exp: 6.4 x σ_{SM}

llb$\bar{b}$ Final State

Higgs signal:
- ZH→llb$\bar{b}$



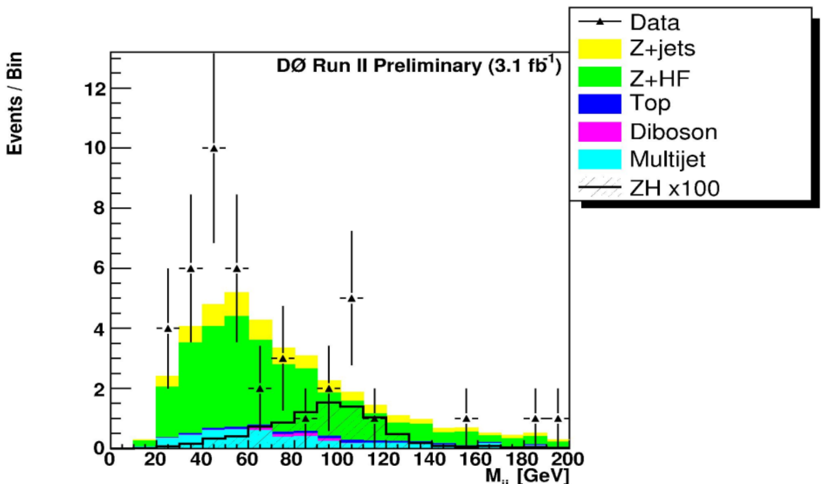
Selection

2 leptons (e/μ): p_T>18,10 GeV (CDF)
p_T>10 (15) GeV for e (μ) (D0)
≥2 Jets: E_T>25,15 GeV, |η|<2.0 (CDF);
E_T>20,15 GeV, |η|<2.5 (D0);

Major backgrounds: Z+jets, t$\bar{t}$, ZZ

- CDF: 6 sub-samples (3 b-tag combinations, loose/tight lepton ID)
- DØ: 2 sub-samples based on b-tagging

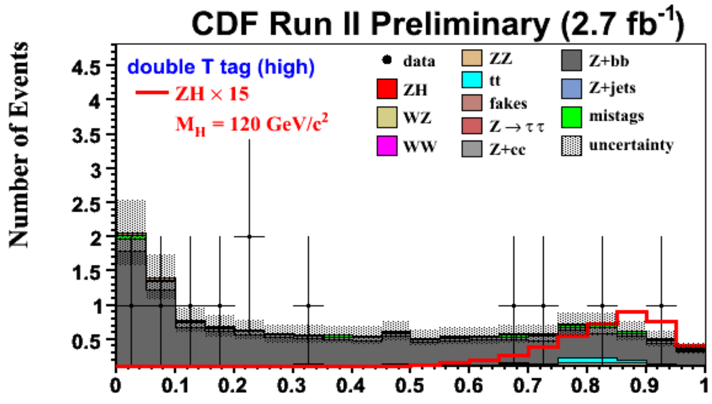
Z , H: fully reconstructed, no real missing E → use constraints to improve m_{jj} resolution:
- CDF: train a NN to correct jets to parton level
- DØ: Perform a kinematic fit



Multivariate discriminators for signal/bg separation in each subsample
- CDF: NN's with 11 inputs and 2 outputs to separate ZH from t$\bar{t}$ and Z+b$\bar{b}$
- DØ: Boosted Decision Trees

$ll b\bar{b}$ Final State: Limits

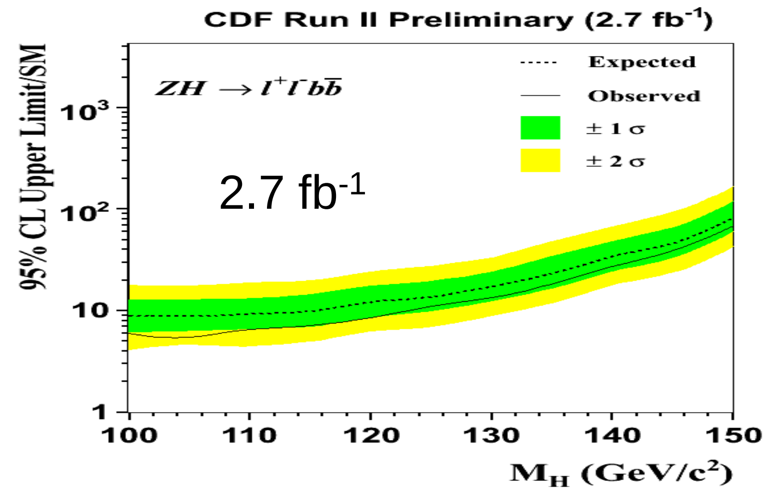
Example output distributions obtained for subsamples

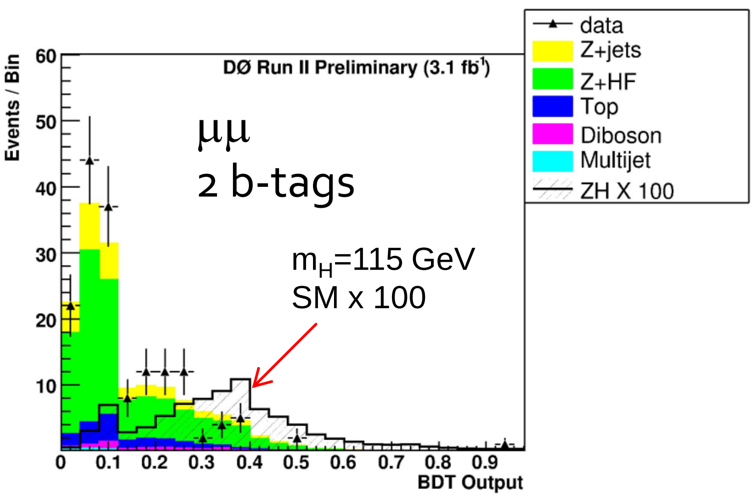


2D NN projection: signal separation from Z+bb

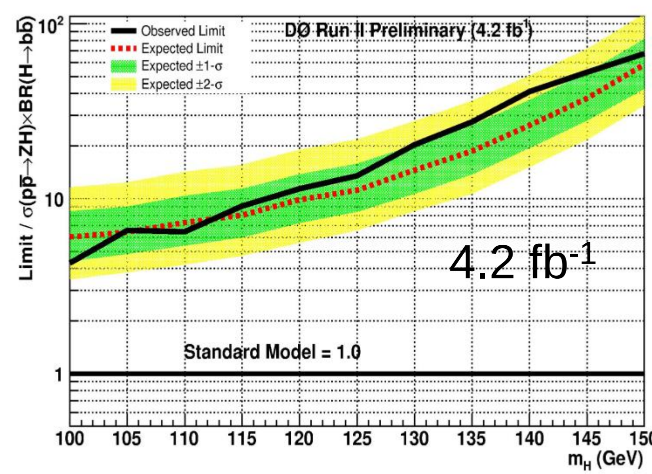
m_H=115 GeV
Obs: 7.1 x σ_{SM}
Exp: 9.9 x σ_{SM}

Expected and observed limits





m_H=115 GeV
Obs: 9.1 x σ_{SM}
Exp: 8.0 x σ_{SM}

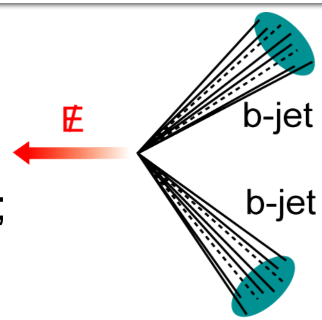


MET+$b\bar{b}$ Final State

Selection

MET>50 GeV

≥2 Jets: E_T>35,20 GeV, |η|<2.0 (CDF);
E_T>20 GeV, |η|<2.5 (D0);



Higgs signal:

- $ZH \to \nu\bar{\nu}b\bar{b}$
- $WH \to l\nu b\bar{b}$ (undetected lepton)

Main backgrounds: multi-jet, W/Z+jets, $t\bar{t}$

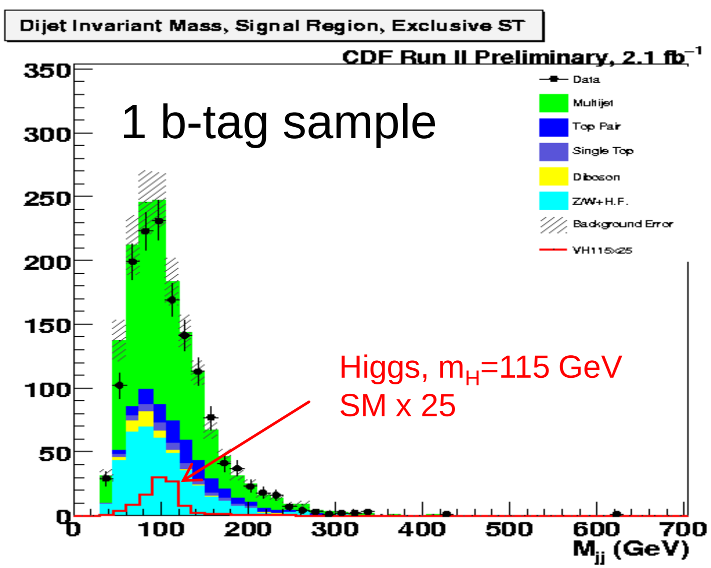
- The major challenges are multi-jet background estimation and suppression
  - Use data-driven techniques
  - Cross-checks in control regions

Signal extraction

- CDF: Neural network
- DØ: Boosted Decision Tree

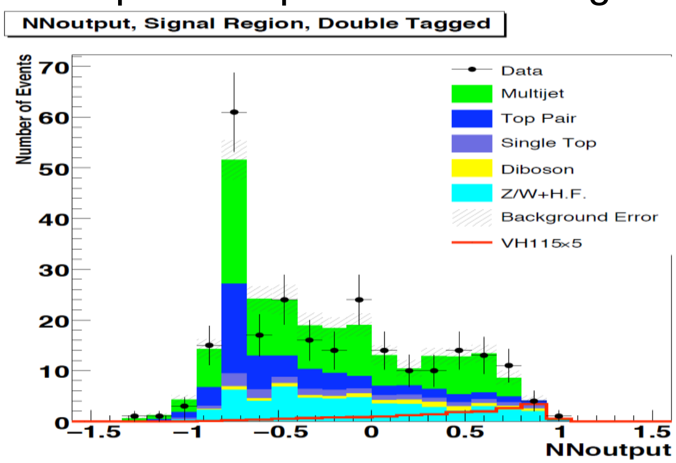
- CDF: 3 sub-samples based on b-tag requirements

Di-jet mass (CDF)

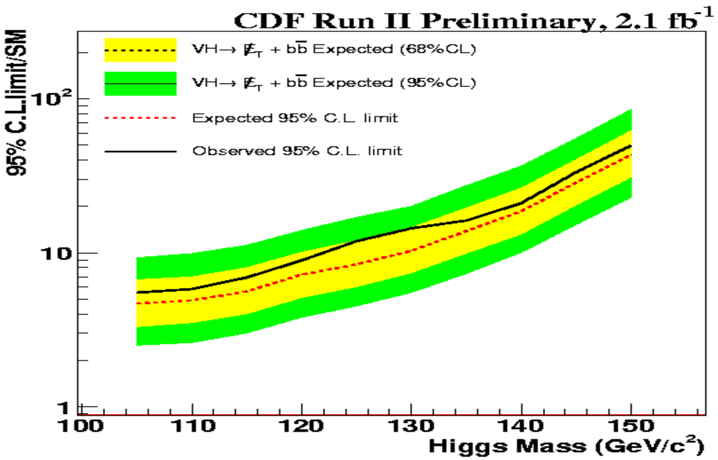


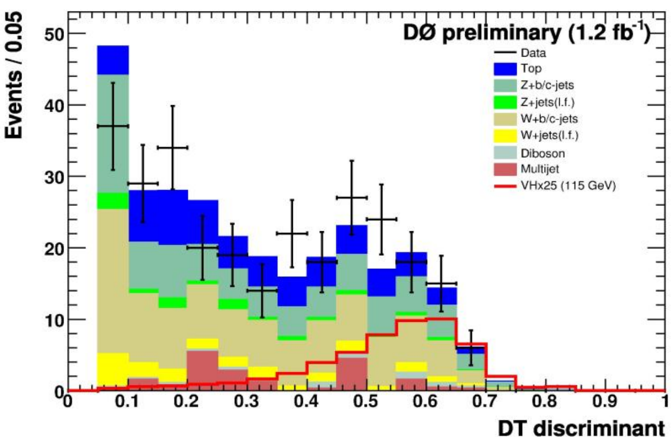
MET+$b\bar{b}$ Final State: Limits

NN output: sample with two b-tags

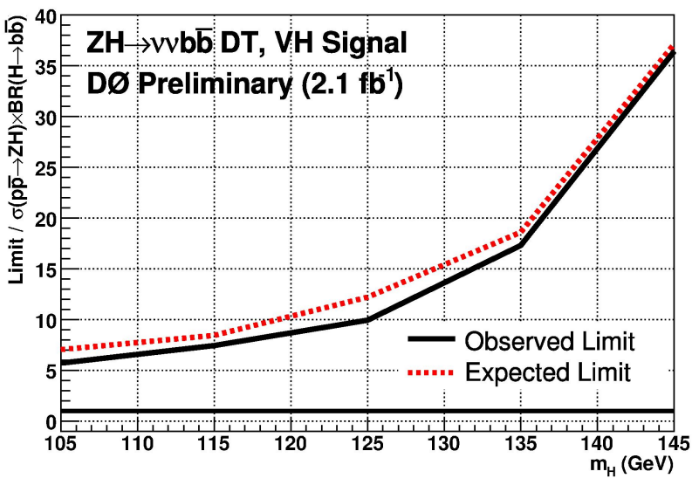


m_H=115 GeV
Obs: 6.9 x σ_{SM}
Exp: 5.6 x σ_{SM}



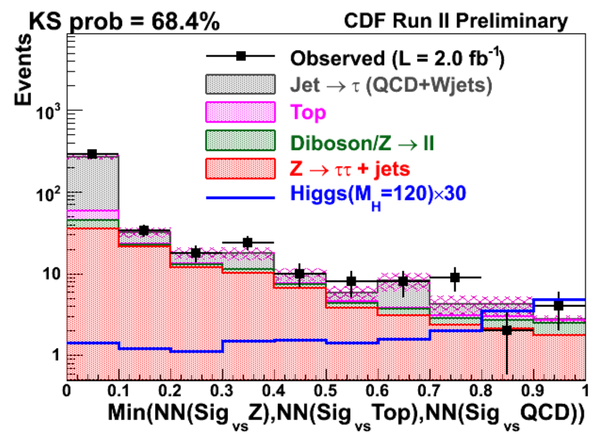


m_H=115 GeV
Obs: 7.5 x σ_{SM}
Exp: 8.4 x σ_{SM}



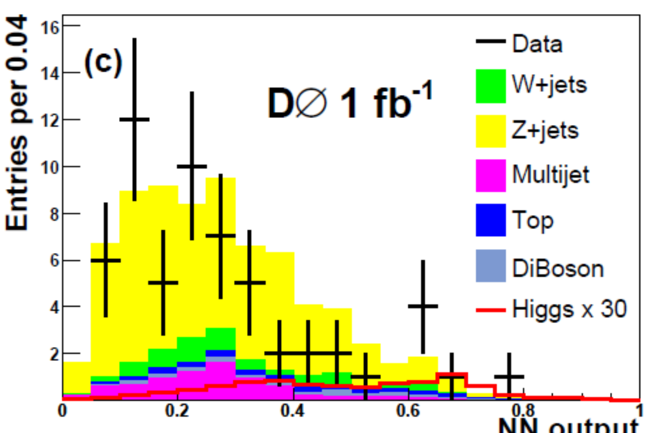
Searches in the H→ττ channel

H→ττ: second largest BR in low-mass region
Select events with ττ+jj final state:
Sensitive to VH→qqττ,, qqH→qqττ, gg→H→ττ (+ ISR)



CDF search (2 fb^{-1})

- 2 taus (1 leptonic+1 hadronic decay), ≥2 jets
- Use 3 NN's to separate bg (combine for limit)
- Obs (exp) limit @ 115 GeV: 26 (31) xSM

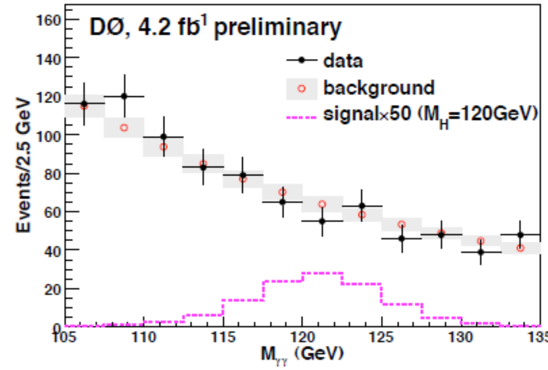


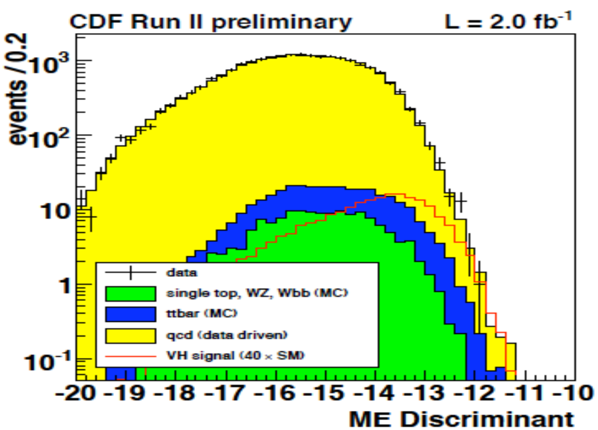
DØ search (1 fb^{-1})

- 2 taus (τ→μνν+1 + hadronic decay), ≥2 jets
- Consider also ZH→ττbb signal
- NN discriminant
- Obs (exp) limit @ 115 GeV: 42 (44) x SM

Additional channels

- DØ search for H→γγ (4.2 fb^{-1})
  - Well-defined signal but small BR
  - Obs (exp) limit @ 115 GeV: 16 (19) x SM



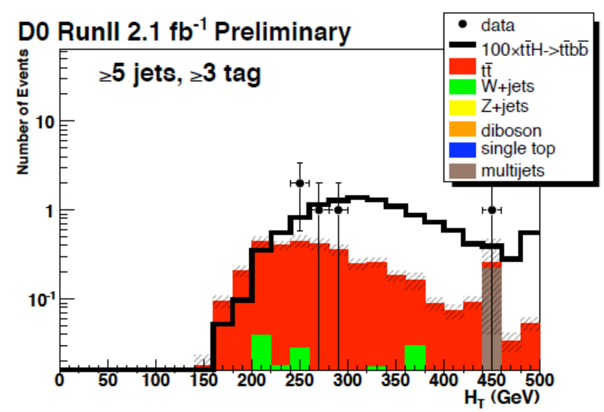


CDF search for W/Z+H→qqbb (2.0 fb^{-1})

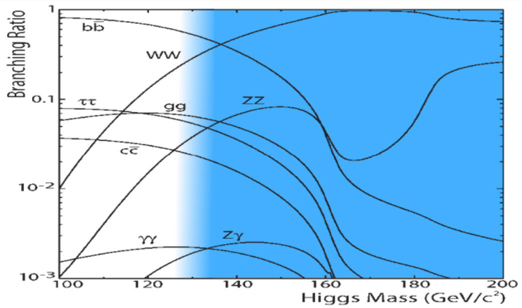
- Multi-jet final state
- Likelyhood ratio using ME
- Obs (exp) limit @ 115 GeV: 37 (38) x SM

DØ search for ttH, H→bb (2.1 fb^{-1})

- ≥5 jets with ≥3 b-tags
- Extract signal from H_T distribution
- Obs (exp) limit @ 115 GeV: 64 (45) x SM



High-mass Higgs



- Dominant decay for m_H>135 GeV: H→W*W
- Select leptonic W decays: 2 OS leptons +X signature
- Final states with e/μ : efficient suppression of multi-jets backgrounds
  - Can take advantage of gg→H production
  - Pick some events from W/Z+H, qqH production
- Disadvantages: account only for ~6% of all events (including taus with leptonic decays)
- Backgrounds: DY, WW, WZ, W+jet, Wγ, tt
- Alternative signature in WH→WW*W: 2 SS leptons + X

H→W*W at DØ

- Split the samples based on lepton flavor

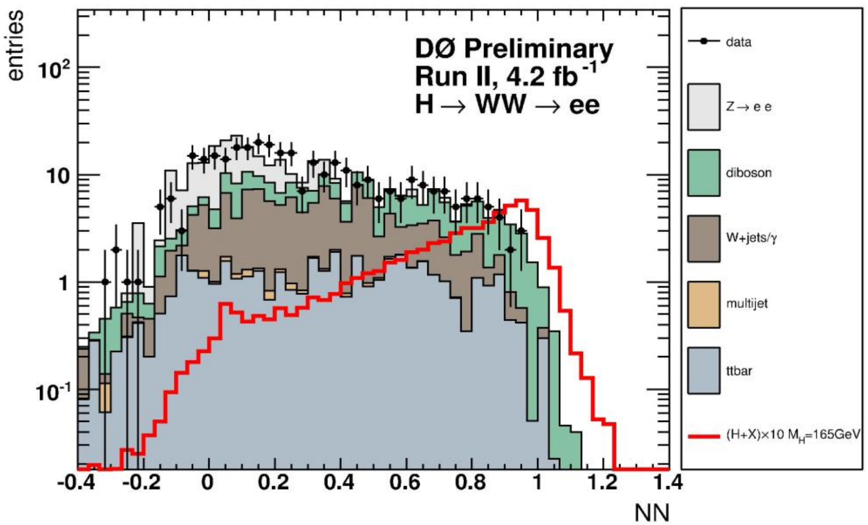
Selection

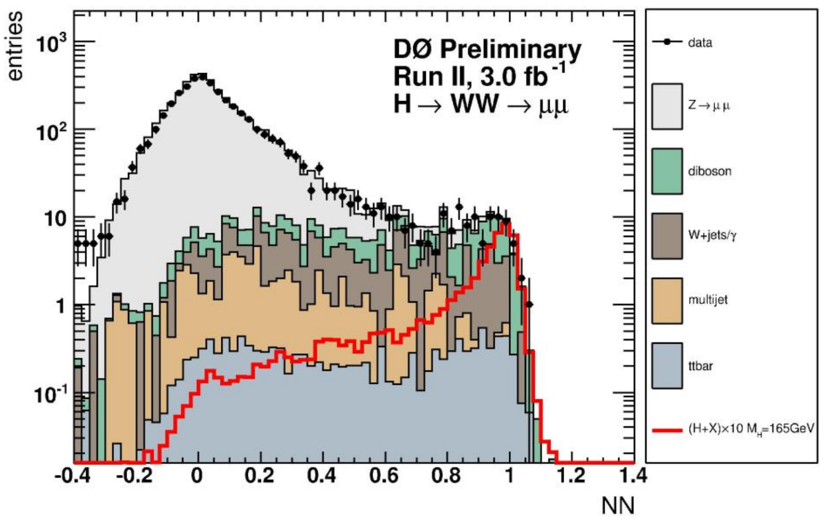
2 leptons (e/μ): p_T>15, 10 GeV
Significant MET
M_{ll}>15 GeV

m_H = 160 GeV; L_{int} = 3.0-4.2 fb^{-1}

Ch.	$\mathcal{L}$ (fb^{-1})	Signal	Bkgd	Data
$e\mu$	4.2	12.2 ± 0.1	337 ± 10	329
ee	4.2	6.13 ± 0.01	332 ± 15	336
$\mu\mu$	3.0	4.85 ± 0.01	4325 ± 24	4084

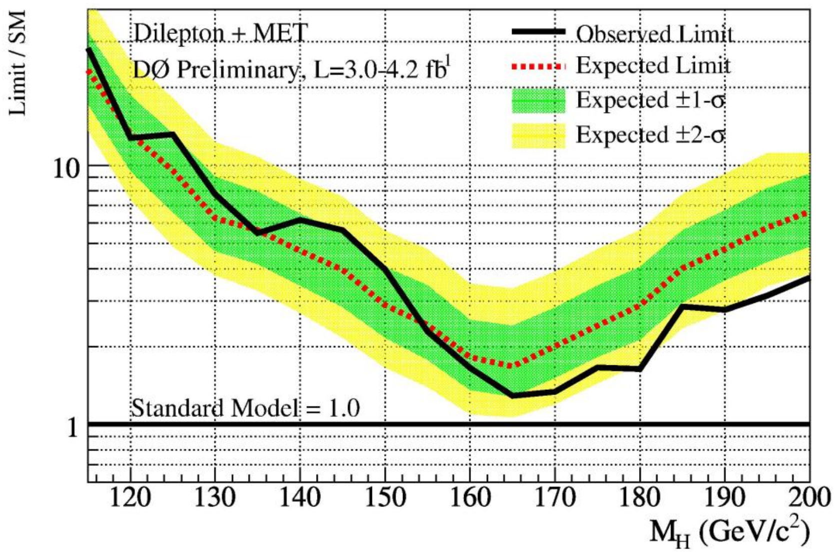
- Neural nets to separate signal from backgrounds





$H \rightarrow W^*W$ at DØ

Limits from the OS di-lepton channel



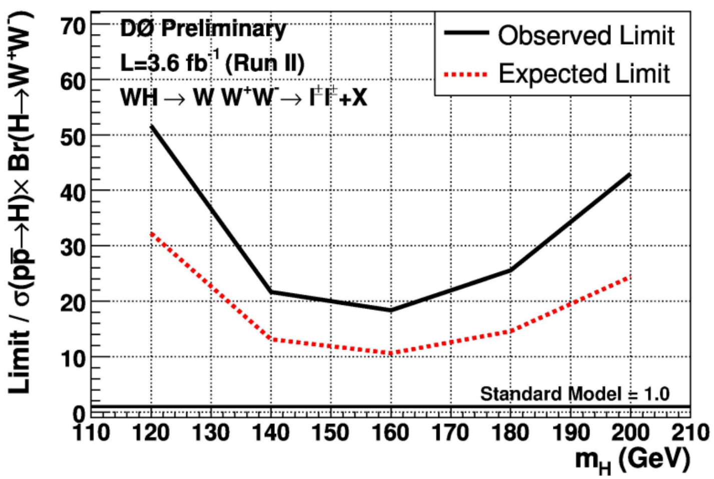
- This channel gets us closest to expected SM signal:

Observed limit = 1.7 x SM @ m_H=160 GeV (expected: 1.8)

- Still no sensitivity for exclusion based on single experiment and channel… but getting there

Increase sensitivity in the $H \rightarrow W^*W$ search: add SS events from $WH \rightarrow WW^*W \rightarrow l^{\pm}l^{\pm}$ +X

- Major backgrounds
  - Charge misidentification
  - W+jets (Jet→lepton misidentification)
- Observed limit = 18 x SM @ m_H=160 GeV (expected: 11)



$H \rightarrow W^*W$ at CDF

Selection

2 leptons (e/μ): p_T>20, 10 GeV
Significant MET; M_{ll}>16 GeV

m_H = 160 GeV; L_{int} = 3.6 fb^{-1}

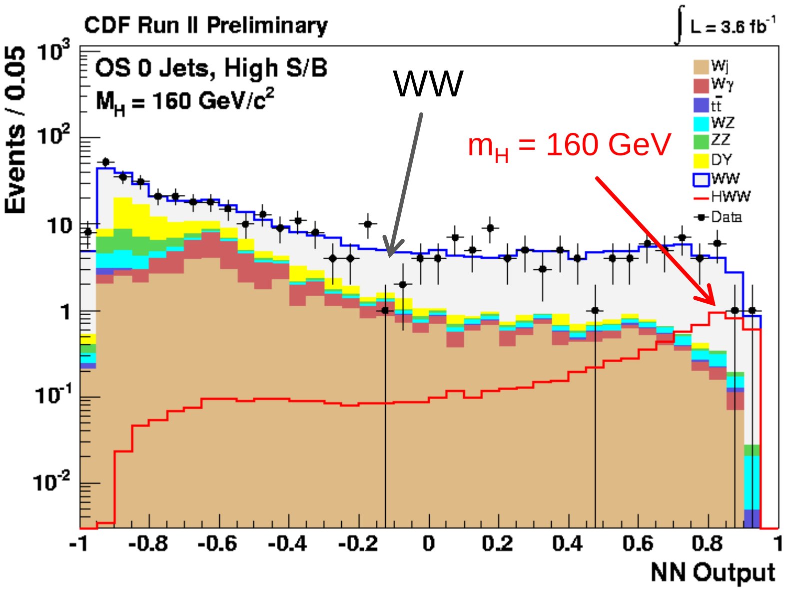
Channel	Signal	Bkgd	Data
0 Jets	9.5 ± 1.4	637 ± 67	654
1 Jet	5.98 ± 0.78	278 ± 35	262
2+ Jets	4.53 ± 0.52	173 ± 23	169

- Split the samples based on jet multiplicity: different signal and bg composition
- Separate treatment of forward leptons for 0,1 jets

- Higgs production mechanisms have also different expected signal contribution to the subsamples:
  - N_{jets}=0 almost exclusively due to ggH
  - N_{jets}=1 ~20% from VH and VBF
  - N_{jets}≥2 ~60% from VH and VBF

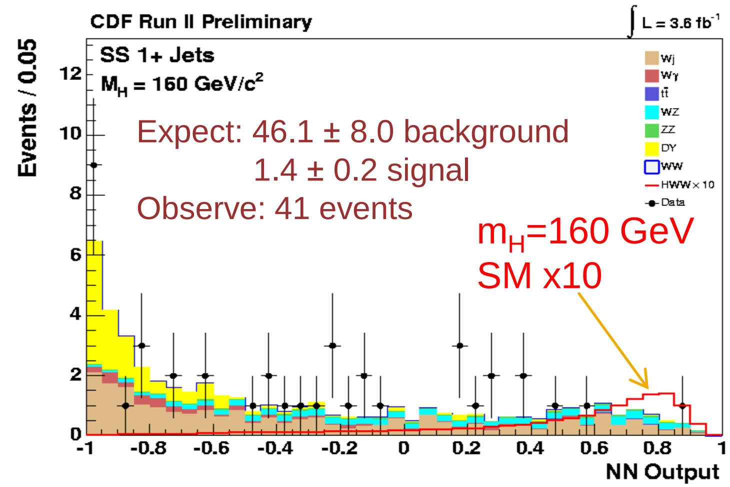
Signal extraction using NN's

- Use kinematic variables as inputs, for zero jets include also the matrix element LR's
- Separate nets for each subsample and mass point

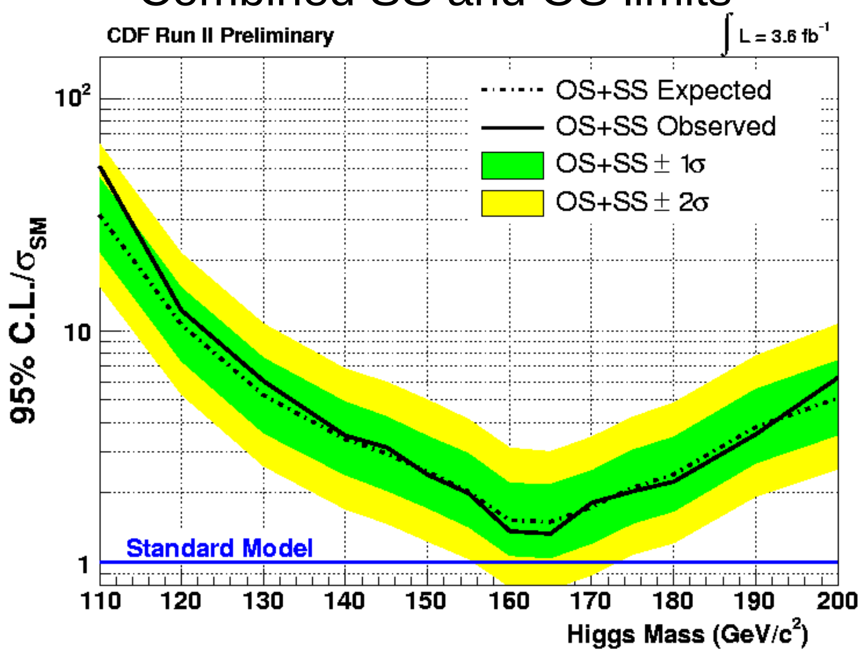


$H \rightarrow W^{*}W$ at CDF

- Select 2 SS leptons and ≥1 jet
- Use a NN to discriminate backgrounds
- Less sensitive than the OS search, but adds ~5% sensitivity



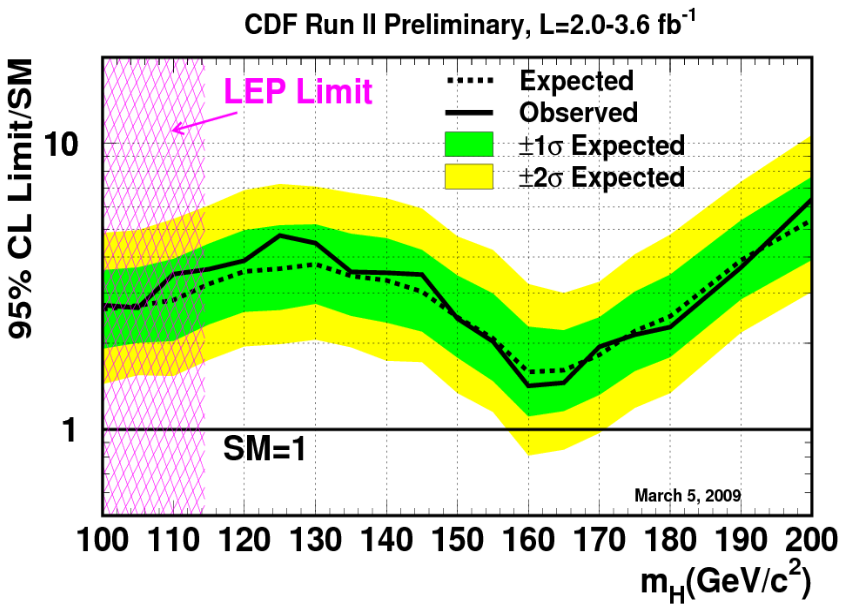
Combined SS and OS limits

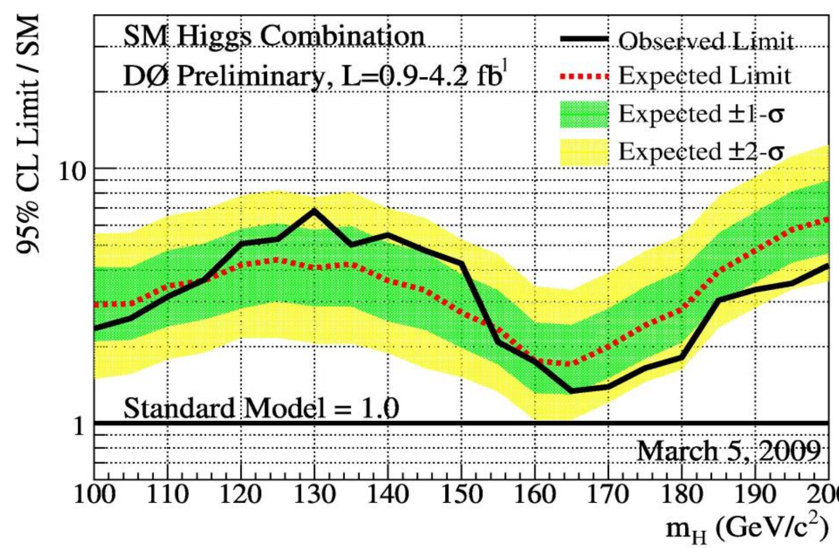


Observed limit: 1.5 x SM prediction @ m_H=160 GeV (expected: 1.4)

(combined OS+SS searches)

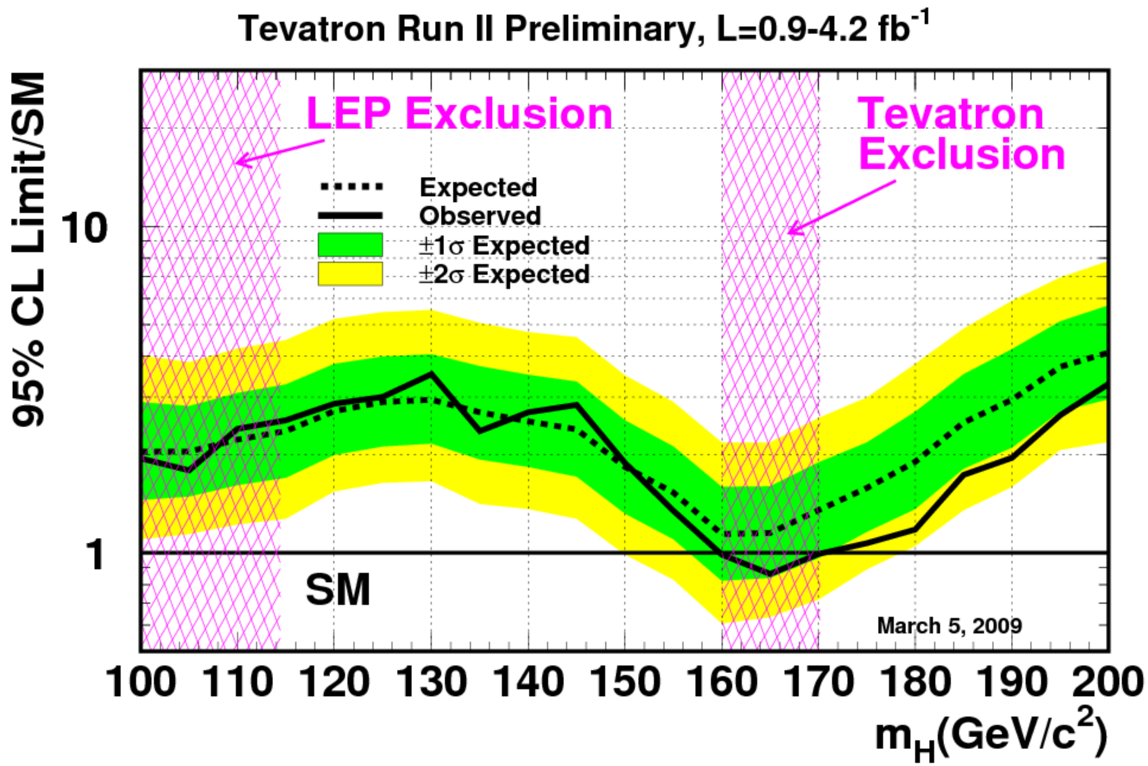
Combined Results for All Masses





- The results are based on L_{int} of 2.0-3.6 (0.9-4.2) fb^{-1} for CDF (DØ)
- Similar overall sensitivity at both experiments
- Maximize sensitivity: combine CDF and DØ results

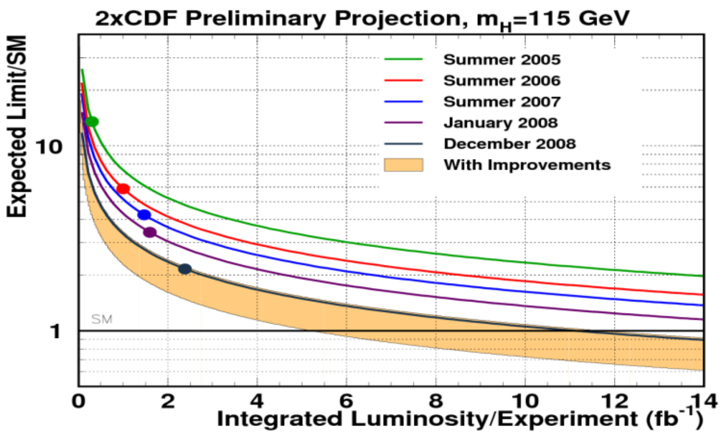
Combined CDF+DØ Limits

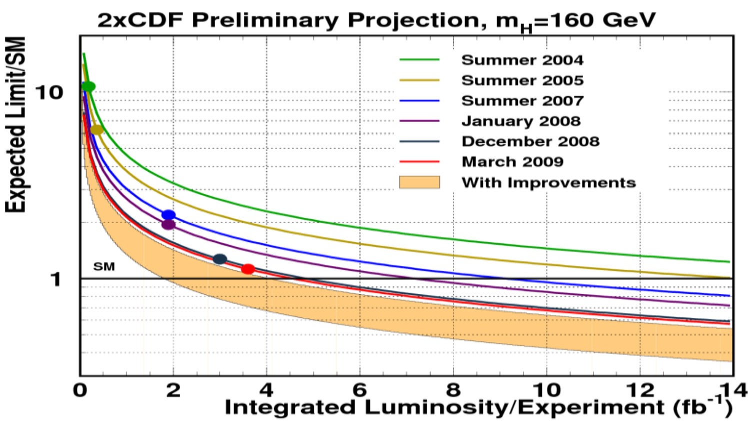


- The Tevatron experiments are now in position to put constraints on the SM Higgs from direct searches
- **SM Higgs with 160<m_H<170 GeV excluded at 95% CL**

Conclusion: What does the (near) future hold

- More data:
  - Collected samples already exceeding 5 fb^{-1} / experiment
  - Smooth operation of the Tevatron and the detectors
- Improved sensitivity
  - Analysis improvements, additional channels





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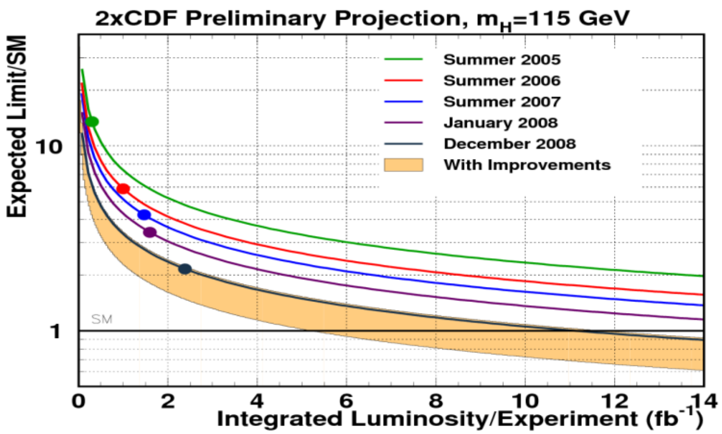
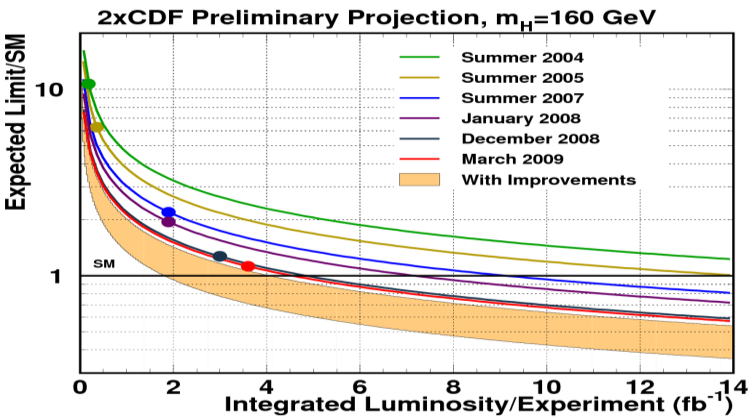
  - Analysis improvements, additional channels





More Higgs news to come from the Tevatron! Keep yourself informed:

http://www-cdf.fnal.gov/physics/new/hdg/hdg.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm