Higgs Searches at the Tevatron

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On behalf of the CDF and DØ Collaborations

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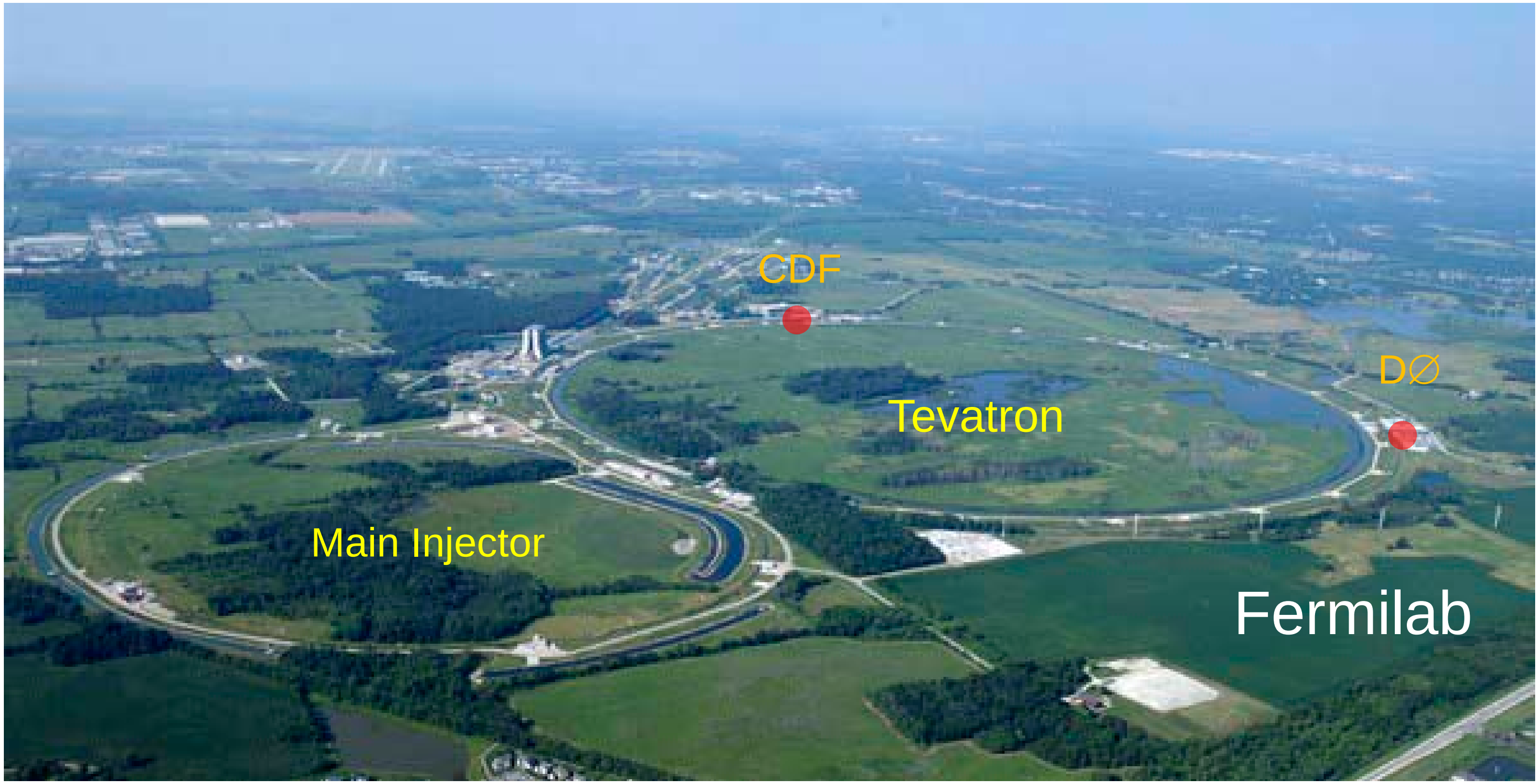
Outline

- Tevatron and Collider Detectors
- Standard Model Higgs Boson
- Higgs Bosons Beyond the SM
- Future Prospects
- Conclusion

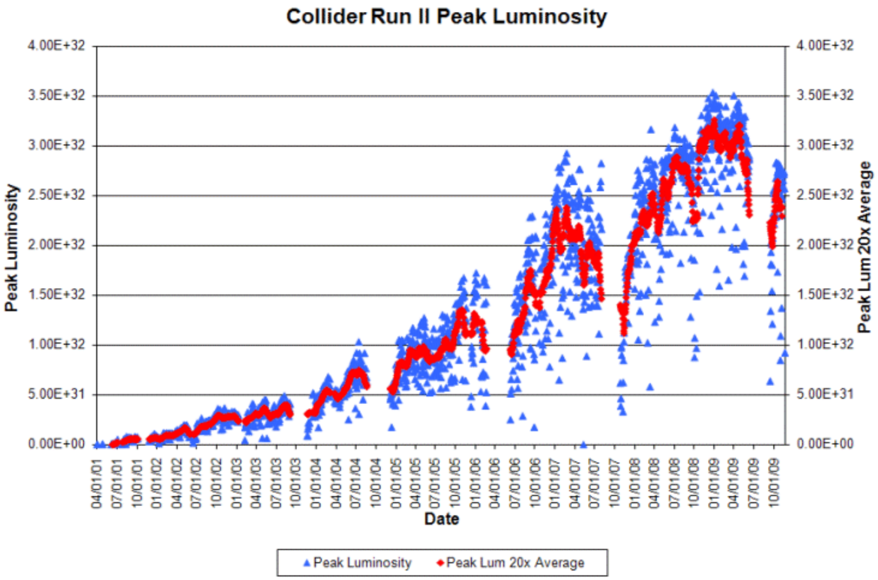
The Tevatron Accelerator

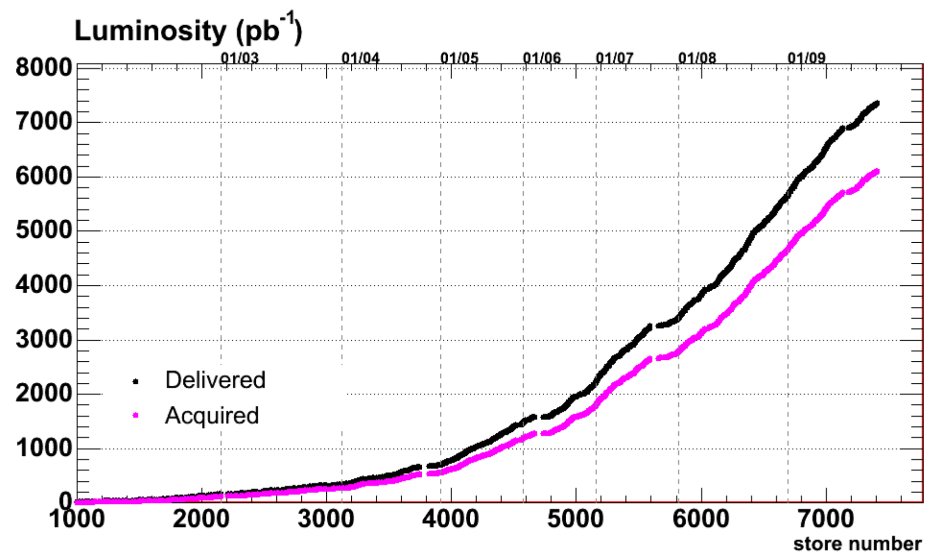
- Proton-antiproton collider at $\sqrt{s}$ = 1.96 TeV
- Two major detectors at collision points : CDF and DØ
- Tevatron and all upstream components are running very well.



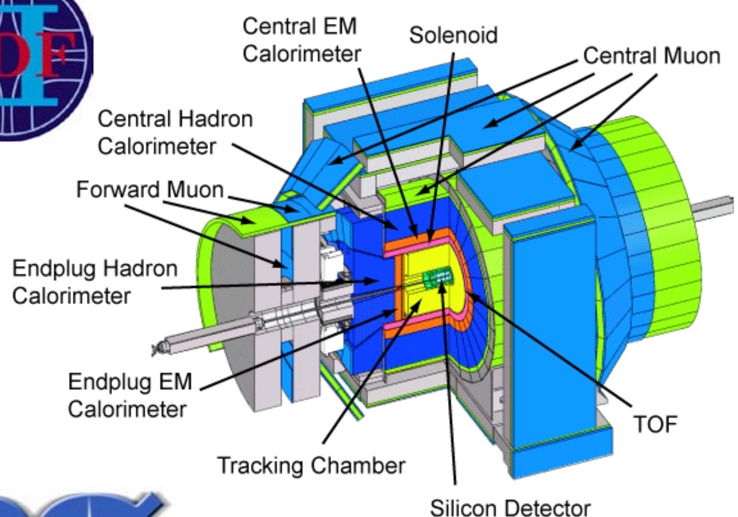
Tevatron Luminosity Progress

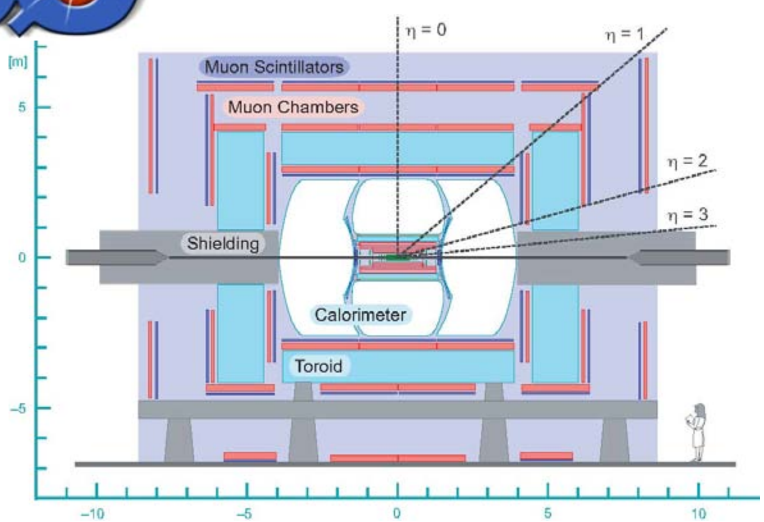
- We are achieving typical luminosity of
  - Peak : ~3 × 10^{32} $cm^{-2}s^{-1}$
  - Weekly integrated : 50~60 pb^{-1}
- Run II record luminosity
  - Peak : 3.7 × 10^{32} $cm^{-2}s^{-1}$
  - Weekly integrated : 74 pb^{-1}
- Integrated luminosity
  - Delivered : 7.4 fb^{-1}
  - Acquired : 6.1 fb^{-1}
  - Analyzed : 5.4 fb^{-1}





Collider Detectors



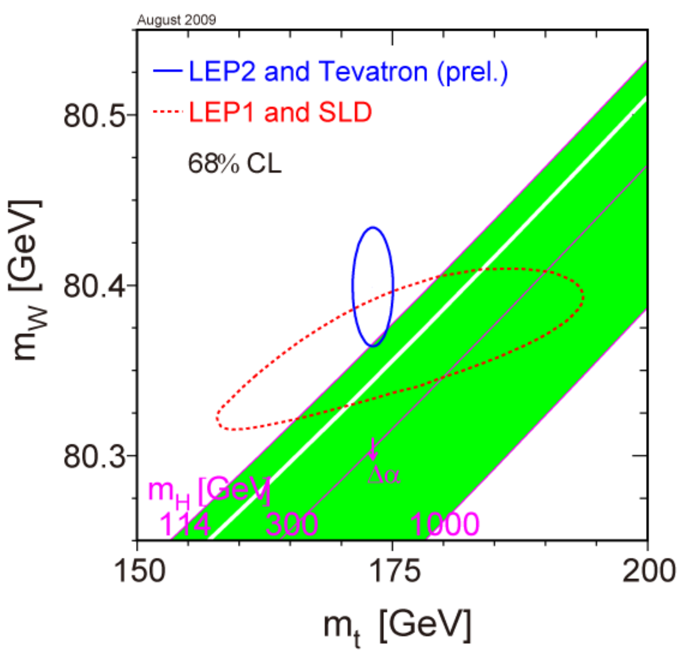


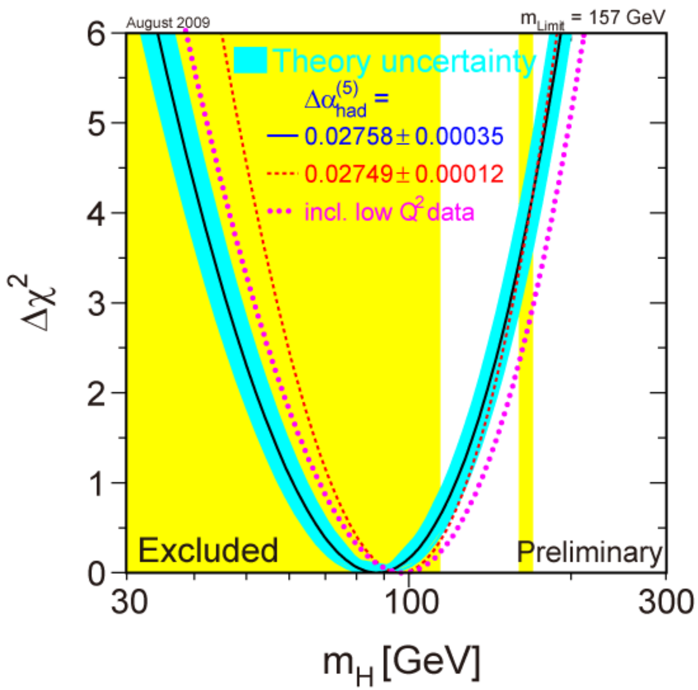
- CDF and DØ
  - General-purpose, cylindrically symmetric detectors
  - Superconducting solenoid magnet
    - 1.4T (CDF) , 1.9T (DØ)
  - Inner detectors for precision tracking
  - Calorimeters for energy measurement
  - Outer muon detectors
  - Well understood, stable operation over a long period of time
  - Accumulated ~6 fb^{-1} of good quality data in both experiments.

Standard Model Higgs Boson

Status of SM Higgs

- Indirect limit from global EW fit
  - $m_t = 173.1 \pm 1.3$ GeV/c^2
  - $m_W = 80.399 \pm 0.023$ GeV/c^2
  - and precision EW measurements at LEP and SLD
  - $m_H = 87^{+35}_{-26}$ GeV/c^2





- Direct search at LEP
  - $m_H > 114.4$ GeV/c^2 (95% C.L.)

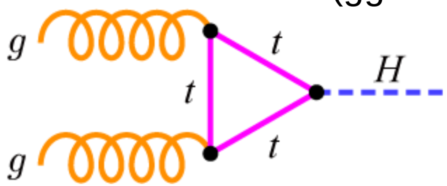
Combining with the limit from EW fit

  - $m_H < 186$ GeV/c^2 (95% C.L.)

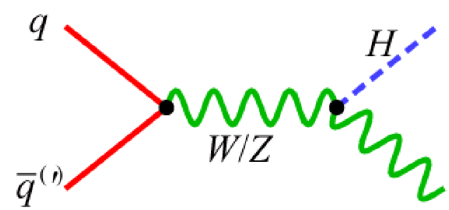
CDF and DØ are probing Higgs in the most probable region : $100 < M_H < 200$ GeV/c^2

SM Higgs Production at Tevatron

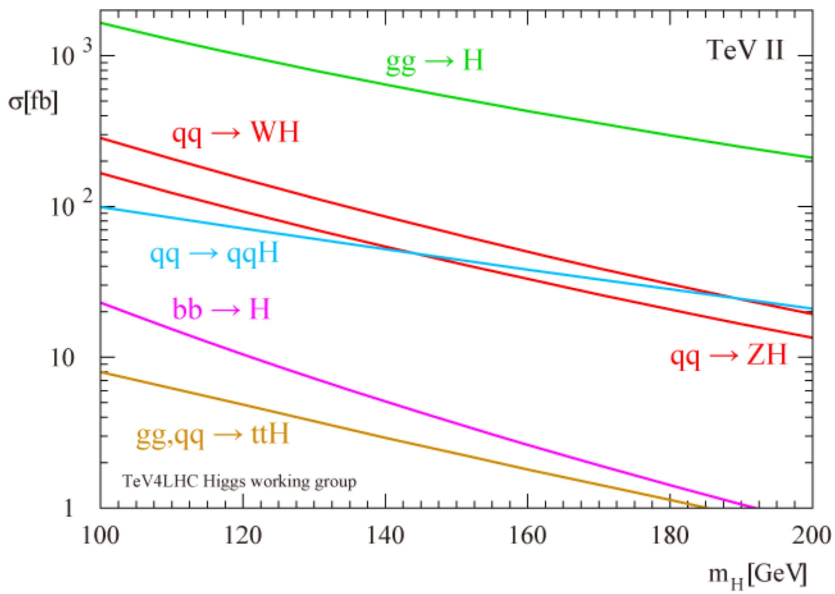
- Following 3 processes are dominant at the Tevatron energy.

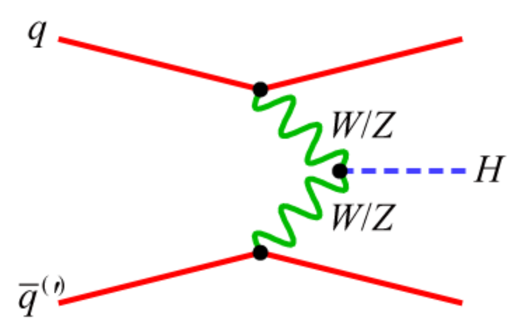


- Gluon fusion
  $\sigma(gg \to H) = 0.2 \sim 1$ pb



- Associated production with a vector boson
  $\sigma(qq \to WH/ZH) = 0.01 \sim 0.3$ pb





- Vector boson fusion
  $\sigma(qq \to qqH) = 0.02 \sim 0.1$ pb

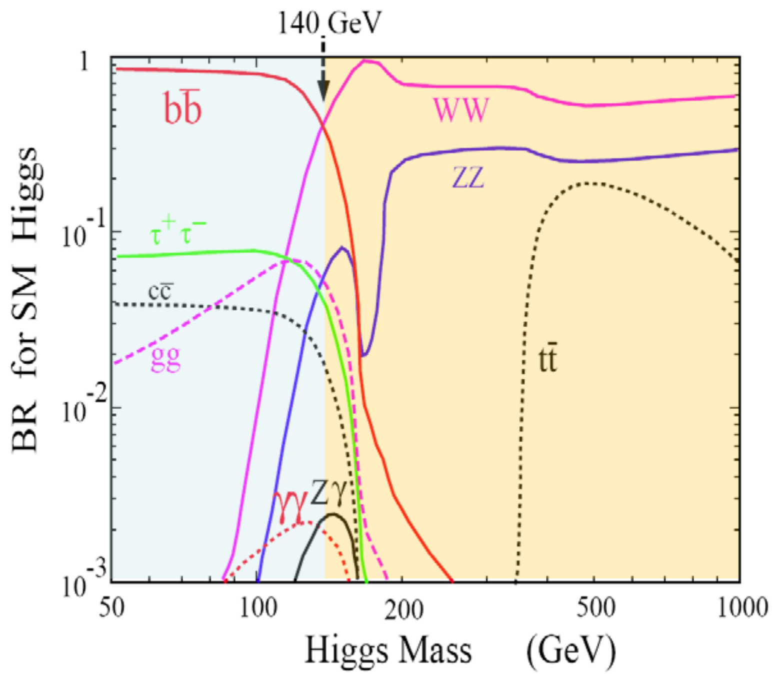
Higgs Decays and Search Channels

- Low mass Higgs (< 140GeV/c^2)
  - bb is dominant.
    - b-tagging is an effective way.
  - gg → H → bb swamps in QCD multijet background.
  - Search in VH production
    - Need triggering with high-p_T lepton or missing E_T

      WH → ℓνbb
      ZH → ℓ⁺ℓ⁻bb, ννbb

- High mass Higgs (> 140GeV/c^2)
  - WW is dominant.
    - Use multi-lepton signature

      gg → H → WW → ℓ⁺ℓ⁻νν



Any single channel does not have enough sensitivity for discovery.

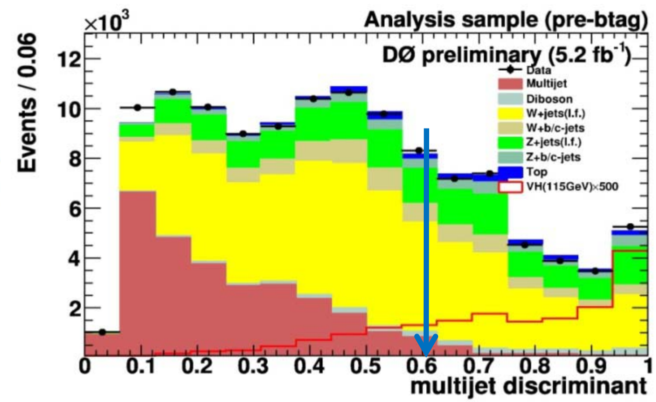
⇓

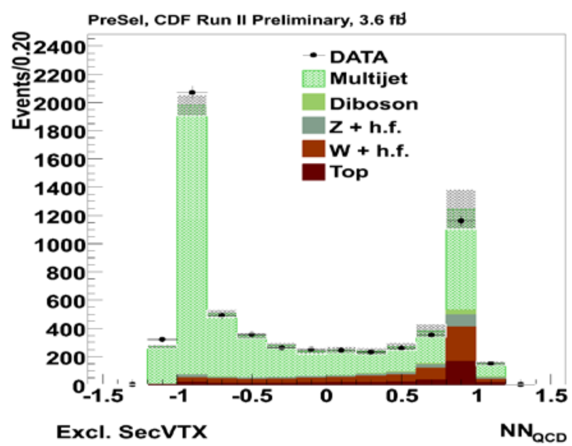
Combine all available channels to gain sensitivity.

VH → $\not\!\!E_T$ bb

- Signature contributed from
  - ZH → ννbb
  - WH → ℓνbb, where ℓ is missing from detector
- Base selection
  - Lepton veto
  - Large missing E_T + 2 or 3 jets
  - At least one b-tagged jet
    - DØ : neural net (NN) tagger
    - CDF : secondary vertex tagger (SECVTX) and jet probability (JP)
- ➢ Background : W/Z+jets, tt, diboson, QCD multijets

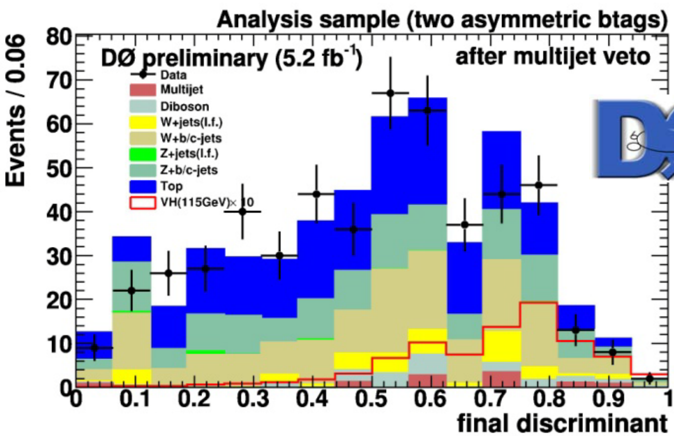
- Remove multijet background by multivariate discriminant
  - DØ : Boosted decision tree (BDT)
  - CDF : NN

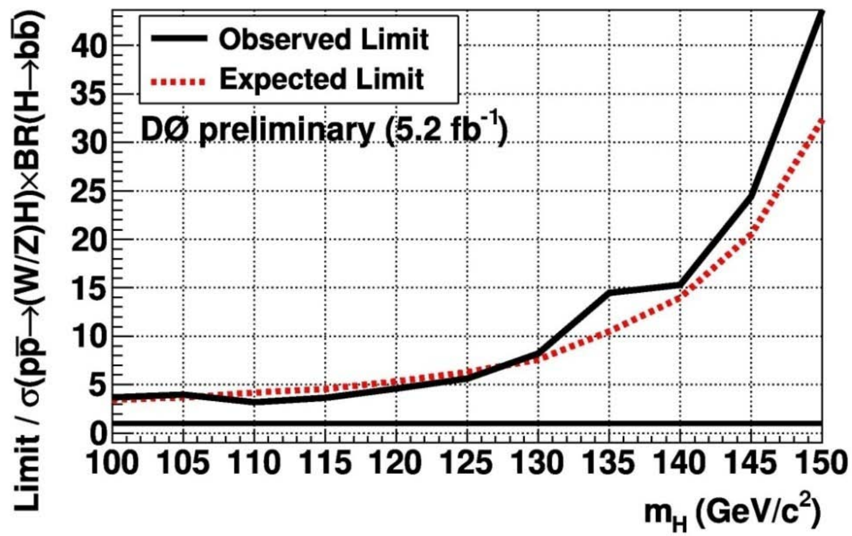


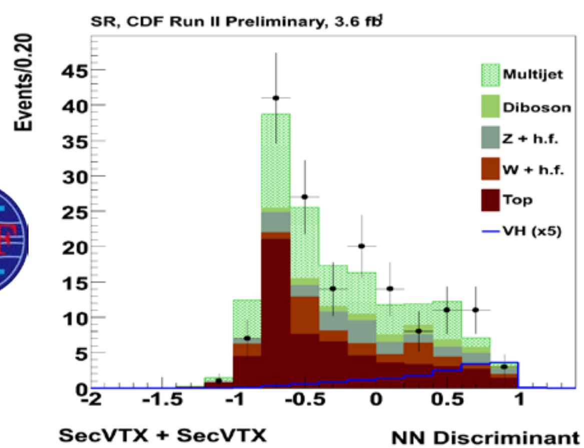


VH → $\not{E}_T$ bb (2)

- Second discriminant to separate signal from other SM background
  - DØ : BDT, CDF : NN







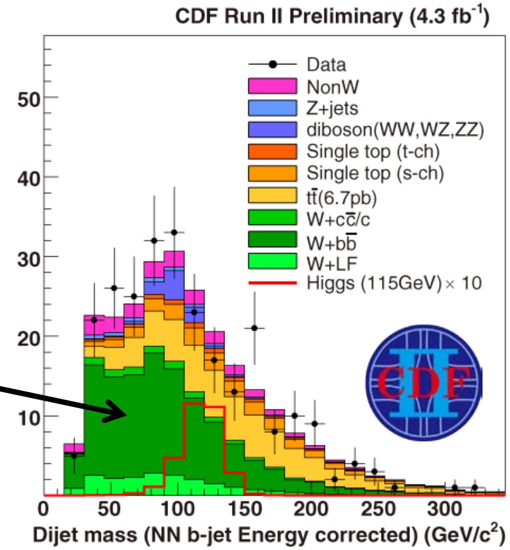
For M_H = 115 GeV/c^2 w/ 5.2 fb^{-1}
Expected limit : 4.6 × σ_{SM}
Observed limit : 3.7 × σ_{SM}

For M_H = 115 GeV/c^2 w/ 3.6 fb^{-1}
Expected limit : 4.2 × σ_{SM}
Observed limit : 6.1 × σ_{SM}

WH → $\ell\nu bb$

- Most sensitive channel at low mass
- Base selection
  - Single isolated high-p_T lepton (e or μ)
  - Large missing E_T
  - 2 or 3 energetic jets
  - At least one b-tagged jet
  - Background : W/Z+jets, tt, single top, diboson, non-W QCD
    - 2 jets – Wbb dominates.
    - 3 jets – tt dominates.

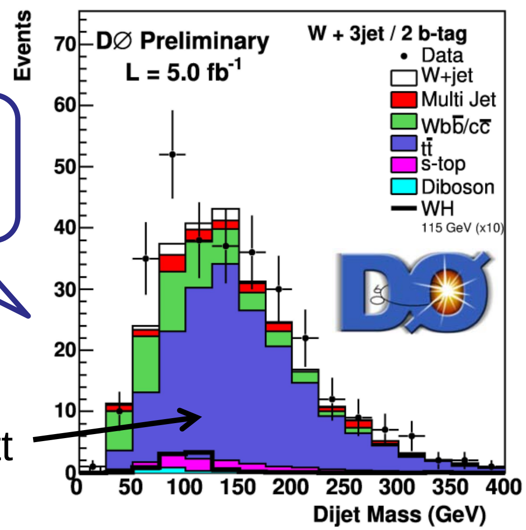
Wbb



Dijet mass (2 jet sample)

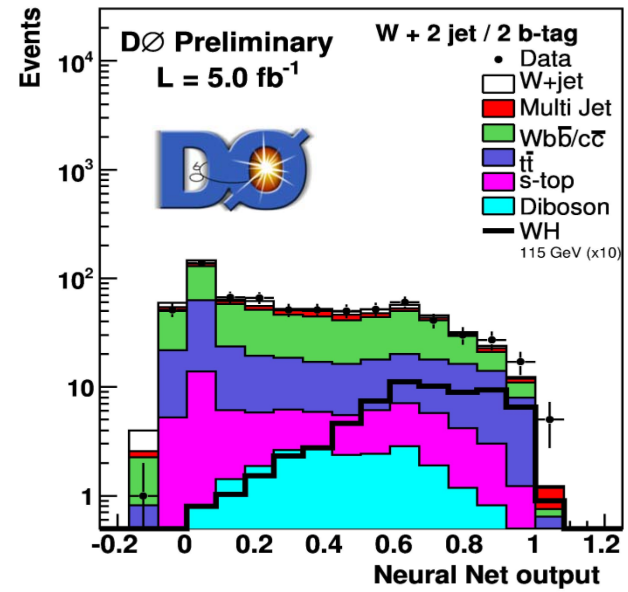
Dijet mass (3 jet sample)

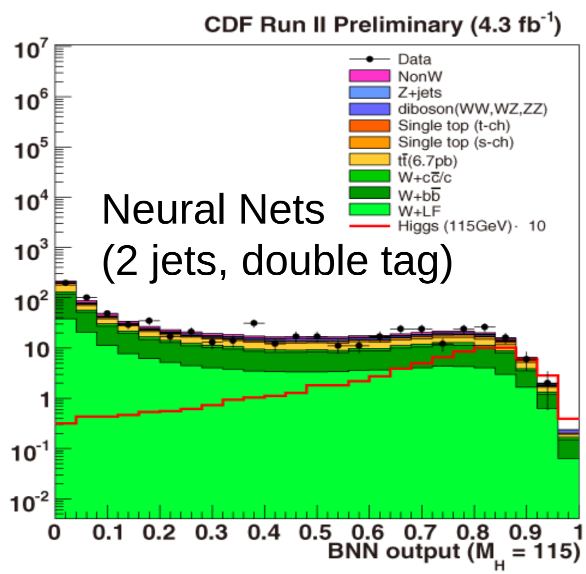
tt

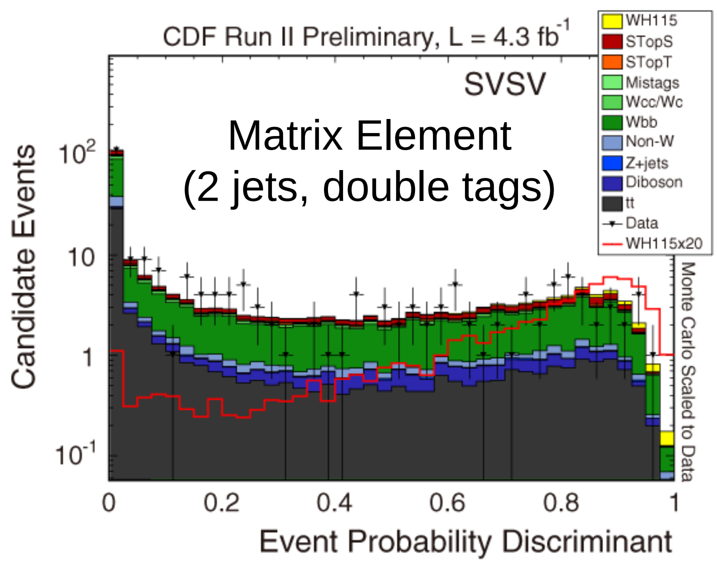


WH → ℓνbb (2)

- Use multivariate discriminant to separate signal from background
  - DØ : Neural Network (NN)
  - CDF : 2 analyses employing NN (2 jets) and ME (2 and 3 jets)
  - ➢ Optimized for b-tag categories

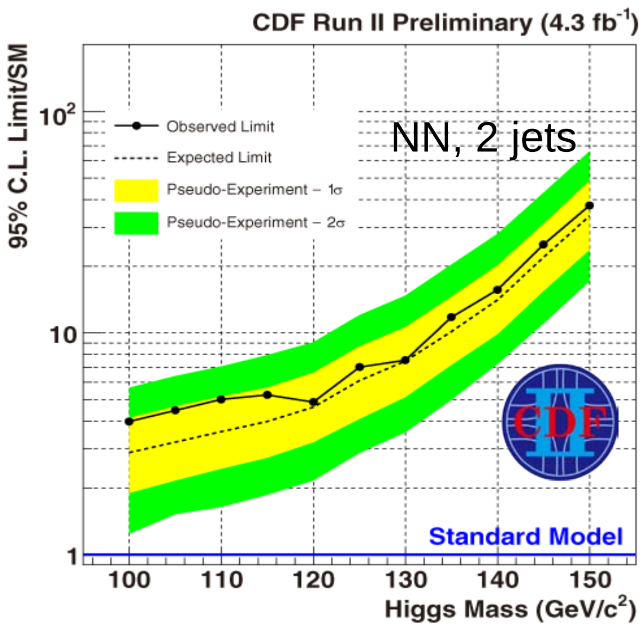


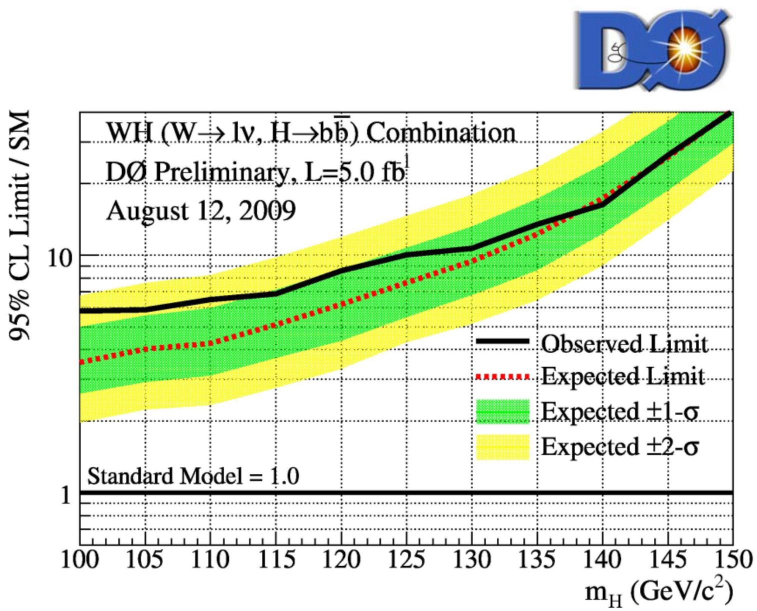




$WH \rightarrow \ell\nu bb$ (3)

- Upper limits on cross section × branching ratio



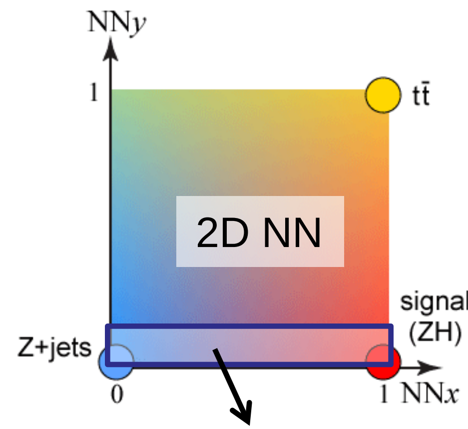


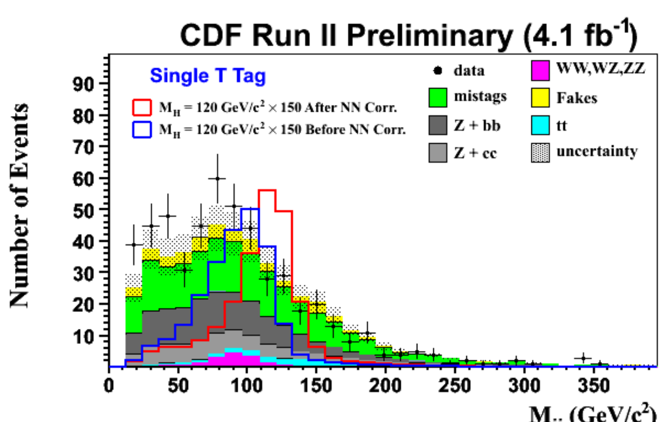
M_H = 115 GeV/c²	Expected limit	Observed limit	Luminosity
CDF (NN, 2 jets)	$4.0 \times \sigma_{SM}$	$5.3 \times \sigma_{SM}$	4.3 fb^{-1}
CDF (ME, full)	$4.1 \times \sigma_{SM}$	$6.6 \times \sigma_{SM}$	4.3 fb^{-1}
CDF (ME, 3 jets)	$18 \times \sigma_{SM}$	$11 \times \sigma_{SM}$	4.3 fb^{-1}
DØ (NN)	$5.1 \times \sigma_{SM}$	$6.9 \times \sigma_{SM}$	5.0 fb^{-1}

ZH → ℓℓbb

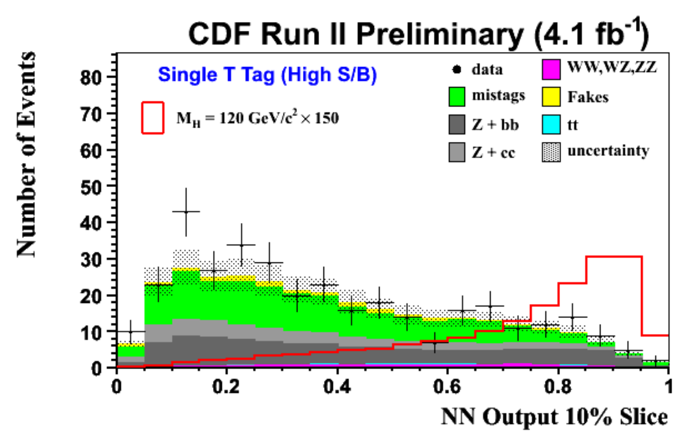
- Clean, but low event rate
- Base selection
  - Z candidates reconstructed from e^+e^- and $\mu^+\mu^-$ pairs
  - 2 or more energetic jets
  - At least one b-tagged jet
- ➢ Background
  - Z+jets(bb, cc, light flavor)
  - tt, WZ, ZZ, QCD fake

- Multivariate discriminant analysis
  - CDF : 2D Neural network
  - DØ : Boosted decision tree



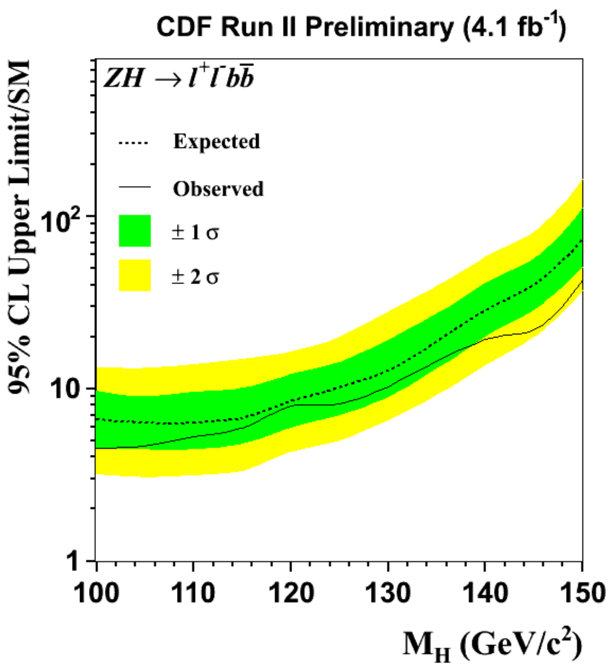


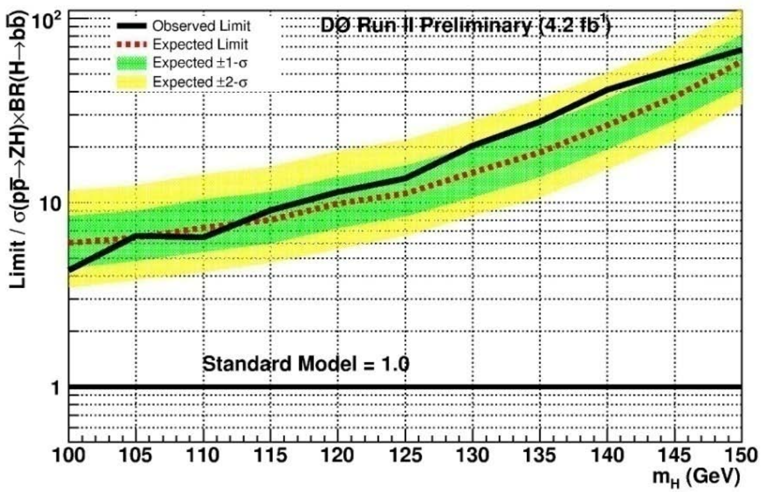
Dijet mass



$ZH \rightarrow \ell\ell bb$ (2)

- We observed no significant excess over the background.
  - Set upper limit on the cross section × branching ratio





For M_H = 115 GeV/c^2 w/ 4.1 fb^{-1}
Expected limit : 6.8 × σ_{SM}
Observed limit : 5.9 × σ_{SM}

For M_H = 115 GeV/c^2 w/ 4.2 fb^{-1}
Expected limit : 8.0 × σ_{SM}
Observed limit : 9.1 × σ_{SM}

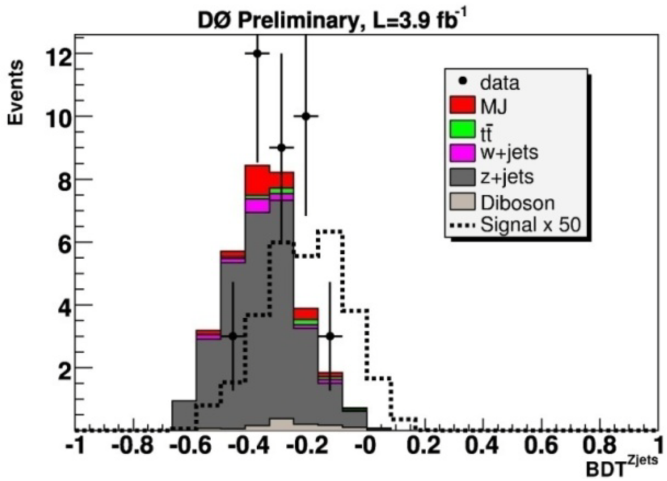
$\tau^+\tau^-$qq final state

- The following 5 processes are involved in $\tau\tau$qq final state.
  - ZH, $Z\to\tau^+\tau^-$, $H\to qq$
  - HZ, $H\to\tau^+\tau^-$, $Z\to qq$
  - HW, $H\to\tau^+\tau^-$, $W\to qq$

    (Associated production)
  - $qq\to Hqq$, $H\to\tau^+\tau^-$ (Vector boson fusion)
  - $gg\to H$, $H\to\tau^+\tau^-$, additional 2jets (Gluon fusion)
- $\tau\tau$ decay identification is essential.
  - Leptonic + hadronic

    e.g.) $\tau^+\tau^- \to (\mu^+ \bar{\nu}_\tau \nu_\mu) + (\pi^-\pi^0\nu_\tau)$
  - 1 or 3 charged particles in a narrow cone.
  - NN is used to identify taus decaying to hadrons.

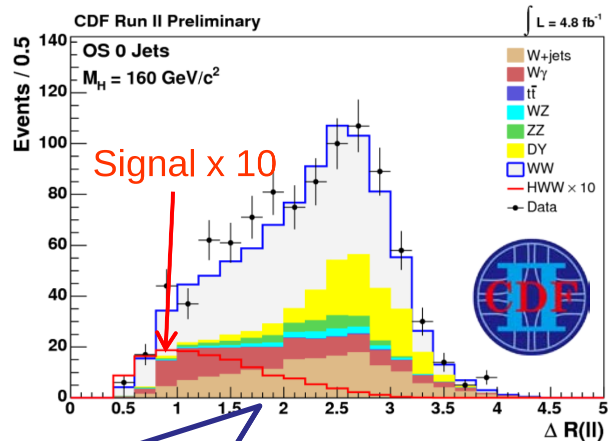
- Signal separation from bkgd is performed with BDT.
  - Background : tt, W/Z+jets, multijets



For M_H = 115 GeV/c^2 w/ 4.9 fb^{-1}
Expected limit : 15.9 $\times$ σ_{SM}
Observed limit : 27.0 $\times$ σ_{SM}

$H \rightarrow WW^*$

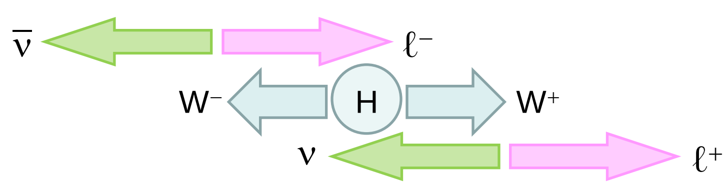
- Sensitive to high mass Higgs (M_H > 140 GeV/c^2)
- Gluon fusion is the dominant production process.
  - $gg \rightarrow H \rightarrow WW^* \rightarrow \ell\ell\nu\nu$
- Some more contributions from WH/ZH and VBF
  - $qq \rightarrow WH \rightarrow WWW^*$
  - $qq \rightarrow ZH \rightarrow ZWW^*$
  - $qq \rightarrow qqH \rightarrow qqWW^*$
- Base selection
  - High p_T opposite-sign dilepton
  - Large missing E_T
  - ➢ Background : tt, Drell-Yan, diboson, W+jets, $W\gamma$



Dilepton opening angle

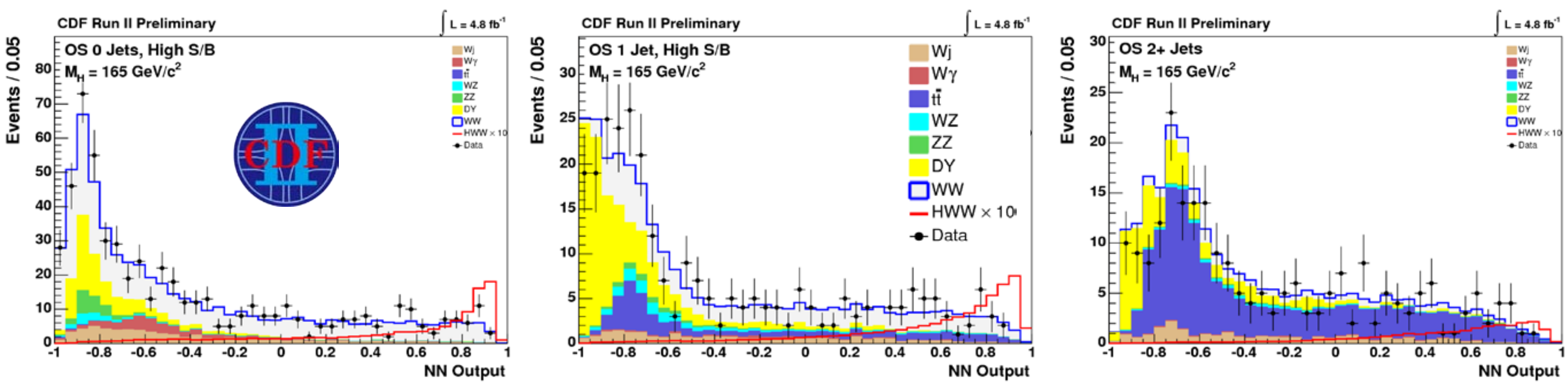
$$\Delta R_{\ell\ell} = \sqrt{(\Delta\eta_{\ell\ell})^2 + (\Delta\phi_{\ell\ell})^2}$$

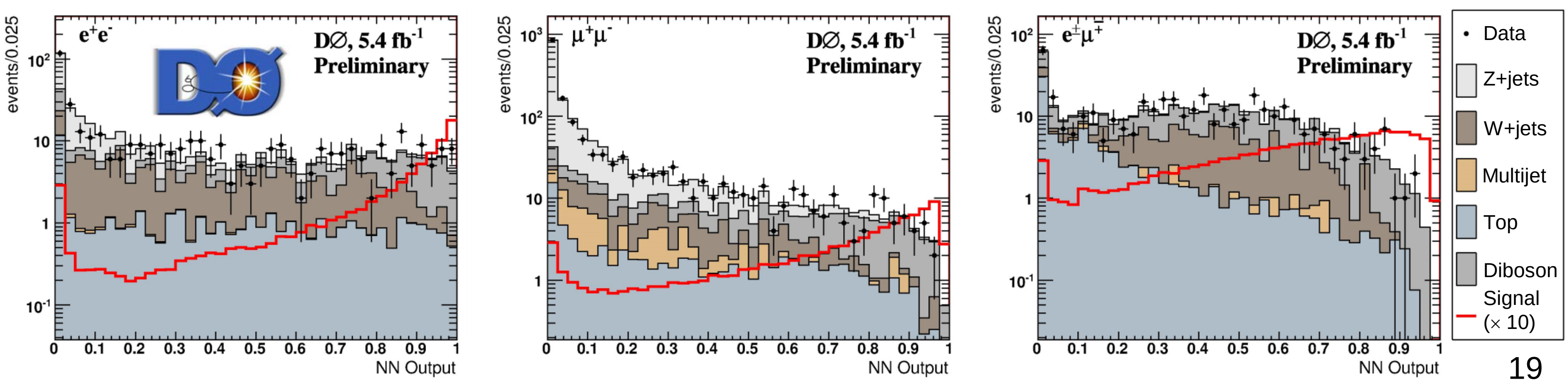
Dileptons from Higgs decay tend to go in the same direction.
- Different from SM backgrounds



H → WW* (2)

- NN is used to distinguish signal from background.
  - Separately trained for different final states
    - CDF : by number of jets (0 jet, 1 jet, 2 or more jets)
    - DØ : by dilepton flavor (ee, μμ, eμ)



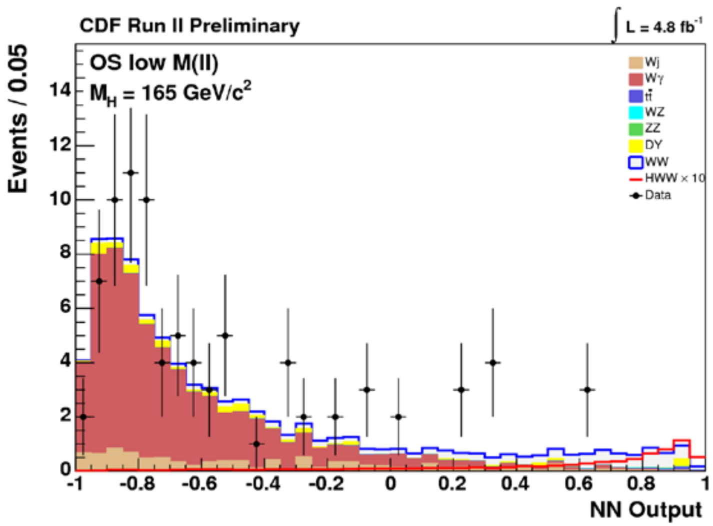


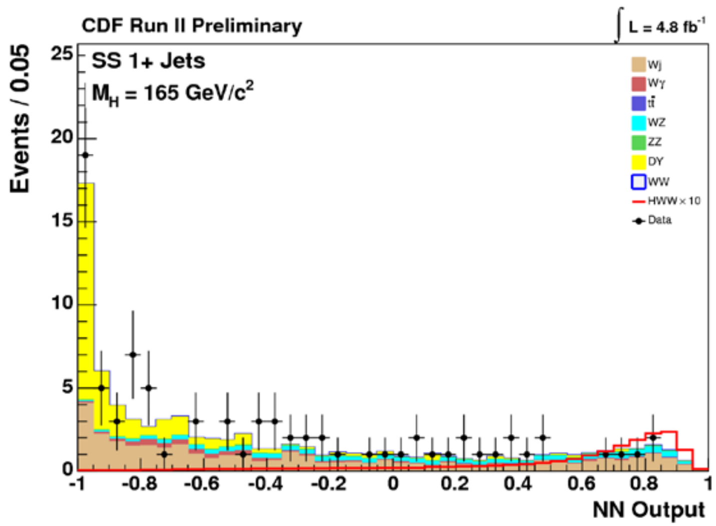
$H \rightarrow WW^*$ (3)

- More samples to increase sensitivity.
  - Low mass ($M_{\ell\ell}$ < 16GeV) region
  - Same-sign dilepton + jets ($WH \rightarrow WWW^*$, $ZH \rightarrow ZWW^*$)

  ➢ Different background composition

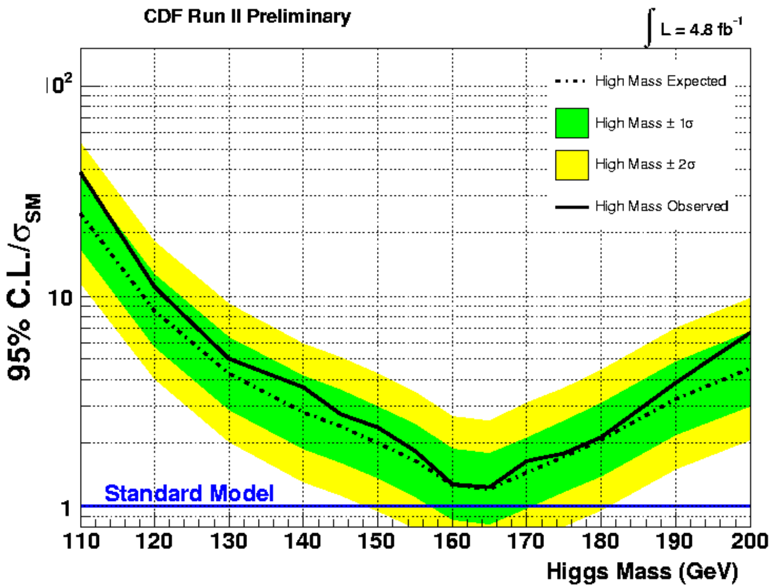
  $\Rightarrow$ Separate NN training

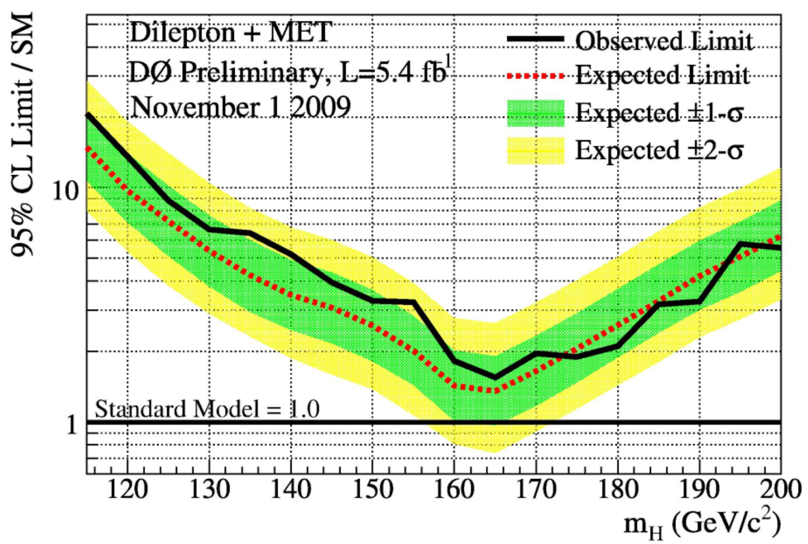




H → WW* (4)

- Expected and observed limits versus Higgs mass for all dilepton channel combination





For M_H = 165 GeV/c^2 w/ 4.8 fb^{-1}
Expected limit : 1.21 × σ_{SM}
Observed limit : 1.23 × σ_{SM}

For M_H = 165 GeV/c^2 w/ 5.4 fb^{-1}
Expected limit : 1.36 × σ_{SM}
Observed limit : 1.55 × σ_{SM}

CDF SM Higgs Combination

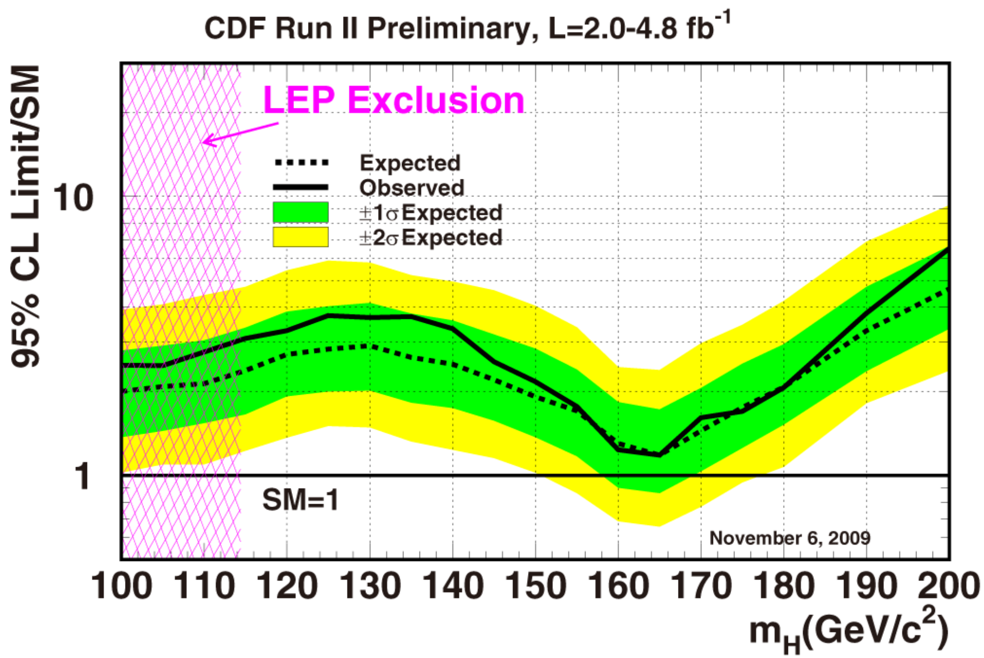
- CDF combined results with $\mathcal{L}$ = 2.0 - 4.8 fb^{-1}

Included channels

WH → $\ell\nu bb$ (4.3 fb^{-1})
VH → $\not{E}_T$ + bb (3.6 fb^{-1})
ZH → $\ell\ell bb$ (4.1 fb^{-1})
VH, VBF, ggH
→ 2 jets + $\tau\tau$ (2.0 fb^{-1})
VH → 2 jets + bb (2.0 fb^{-1})
ggH → WW* → $\ell\nu\ell\nu$ (4.8 fb^{-1})
VH → VWW* (4.8 fb^{-1})

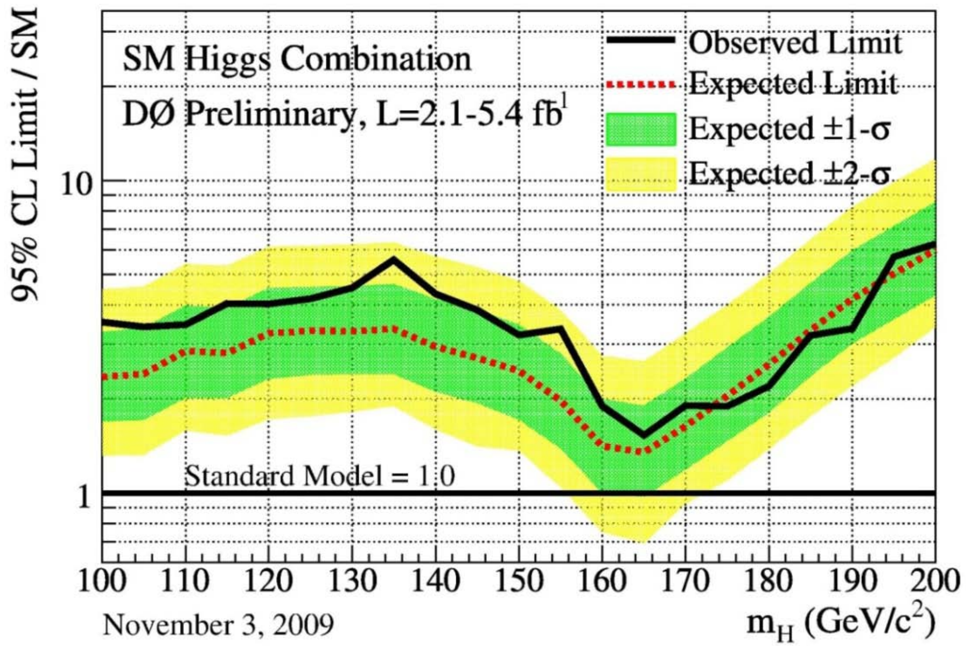
For M_H = 115 GeV/c^2
Expected limit : 2.38 × σ_{SM}
Observed limit : 3.12 × σ_{SM}

For M_H = 165 GeV/c^2
Expected limit : 1.19 × σ_{SM}
Observed limit : 1.18 × σ_{SM}



DØ SM Higgs Combination

- DØ combined results with $\mathcal{L}$ = 2.1 - 5.4 fb^{-1}



Included channels

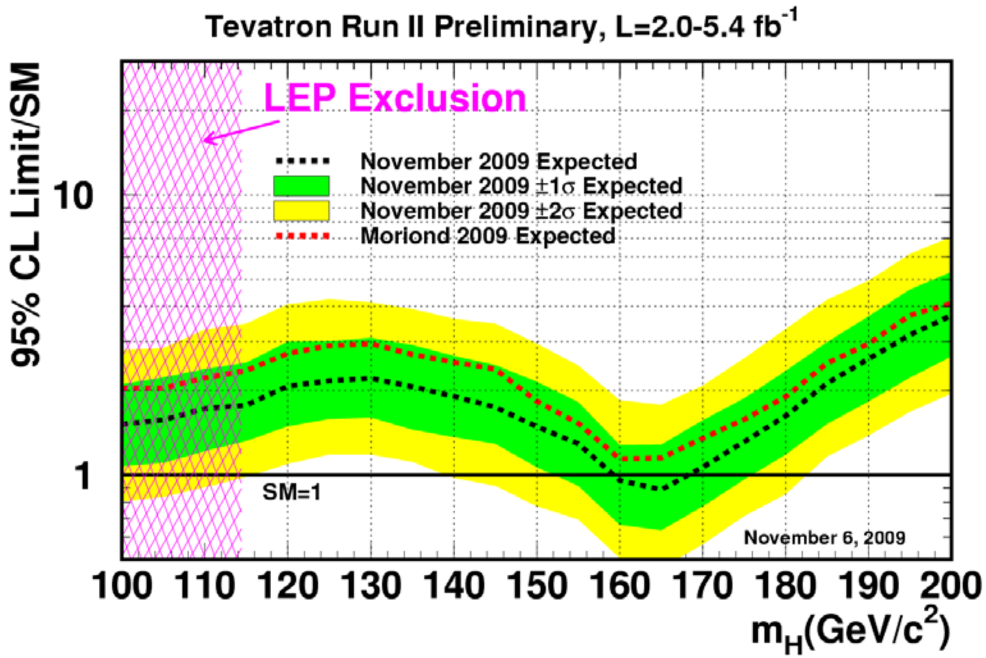
WH → $\ell\nu bb$ (5.0 fb^{-1})
XH → $\tau\tau bb/qq\tau\tau$ (4.9 fb^{-1})
ZH → $\nu\nu bb$ (5.2 fb^{-1})
ZH → $\ell\ell bb$ (4.2 fb^{-1})
WH → WWW* (3.6 fb^{-1})
H → WW* (5.4 fb^{-1})
H → $\gamma\gamma$ (4.2 fb^{-1})
ttH → ttbb (2.1 fb^{-1})

For M_H = 115 GeV/c^2
Expected limit : 2.80 × σ_{SM}
Observed limit : 4.05 × σ_{SM}

For M_H = 165 GeV/c^2
Expected limit : 1.35 × σ_{SM}
Observed limit : 1.53 × σ_{SM}

Tevatron SM Higgs Combination

- Combined results of CDF and DØ with $\mathcal{L}$ = 2.0 – 5.4 fb^{-1}
  - Systematics correlation b/w experiments are taken into account.

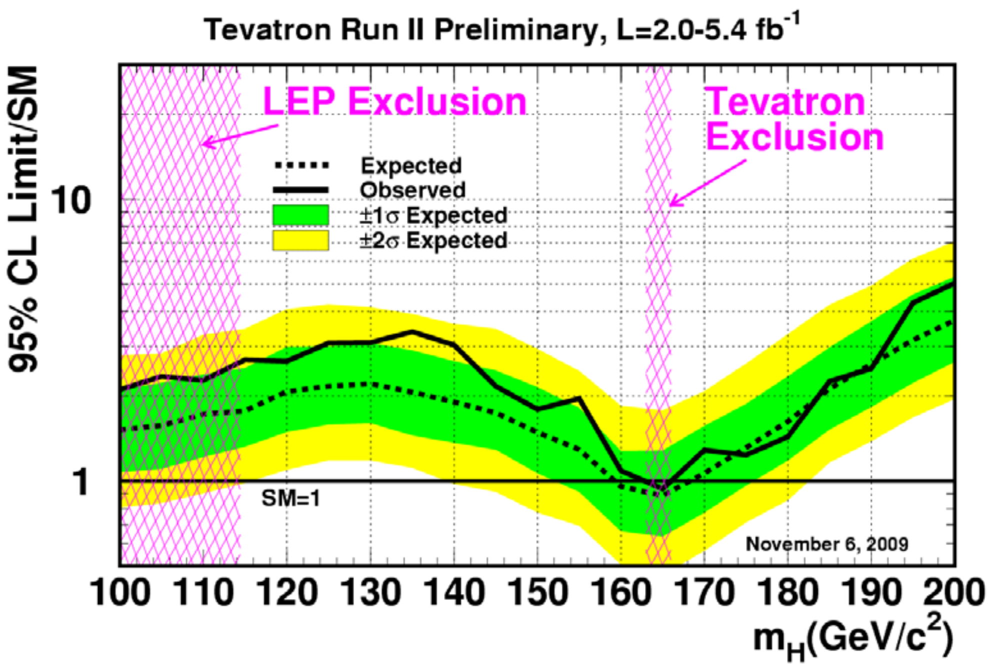


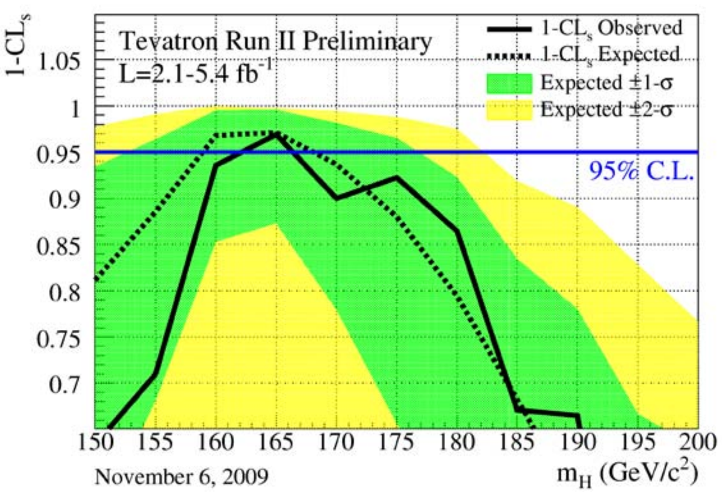
Expected limit at M_H = 115 GeV/c^2 : 1.78 × σ_{SM}

Expected exclusion range at 95% C.L. : 159 – 168 GeV/c^2

Tevatron SM Higgs Combination

- Combined results of CDF and DØ with $\mathcal{L}$ = 2.0 – 5.4 fb^{-1}
  - Systematics correlation b/w experiments are taken into account.





Observed (expected) limit at M_H = 115 GeV/c^2 : 2.70 (1.78) × σ_{SM}
Excluded mass range at 95% C.L. : 163 - 166 GeV/c^2
(Expected exclusion range : 159 – 168 GeV/c^2)

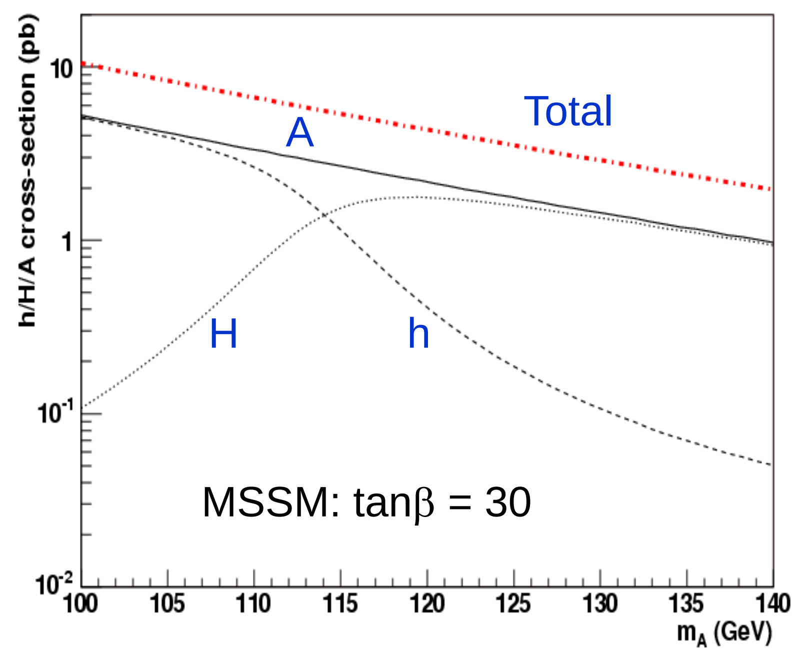
arXiv:0911.3930[hep-ex]

as of November 2009

Higgs Bosons Beyond the SM

MSSM Higgs at the Tevatron

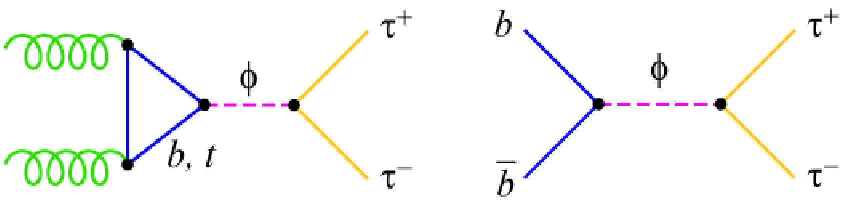
- Two-Higgs-doublet fields provide 5 physical Higgs bosons.
  - 3 neutral : ϕ = h, H, A
  - 2 charged : $H^{\pm}$
  - ➢ Phenomenology described at tree level by $\tan\beta$ and M_A.
- Neutral Higgs
  - Coupling to d-type quarks enhanced by $\tan\beta \Rightarrow \sigma_{\phi} \propto \tan^2\beta$
  - $Br(\phi \to \tau\tau)$ ~10%, $Br(\phi \to bb)$ ~90% for low and intermediate masses
- Charged Higgs
  - For ($M_{H+} < M_t - M_b$), a top quark can decay into $H^{\pm}b$.



Tevatron has sensitivity for some MSSM scenarios.

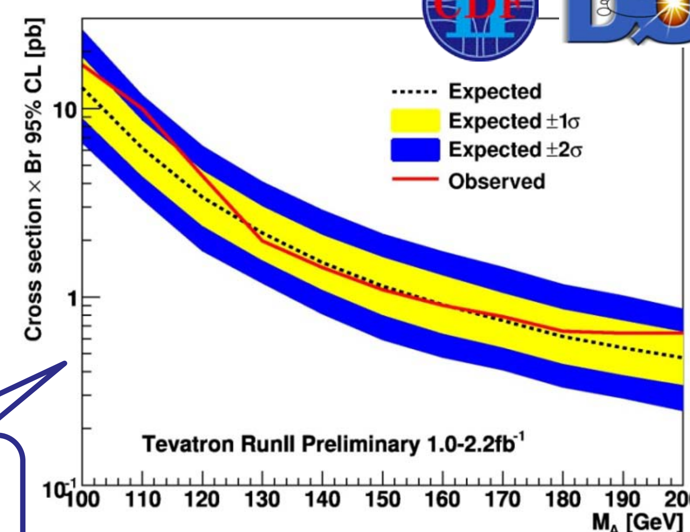
MSSM Neutral Higgs : $\phi \to \tau^+\tau^-$

- $gg, bb \to \phi \to \tau\tau$

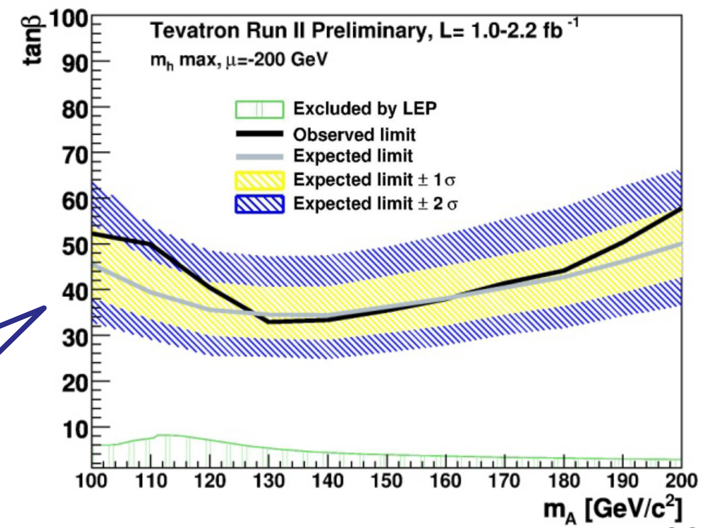


gluon fusion   bb fusion

- Tau pairs are identified in $\tau_e\tau_\mu$, $\tau_e\tau_{had}$, and $\tau_\mu\tau_{had}$.
- Background :
  - $Z \to \tau\tau$, $Z \to ee/\mu\mu$
  - Diboson, tt, W + jets
- Combined CDF and DØ results



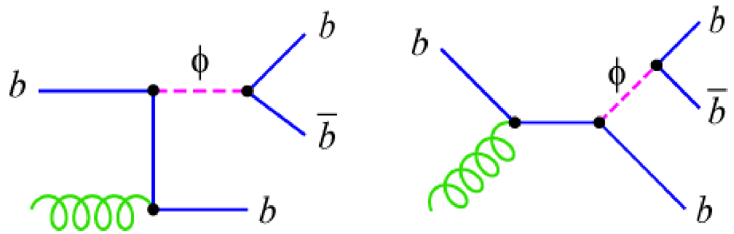
Model independent limit



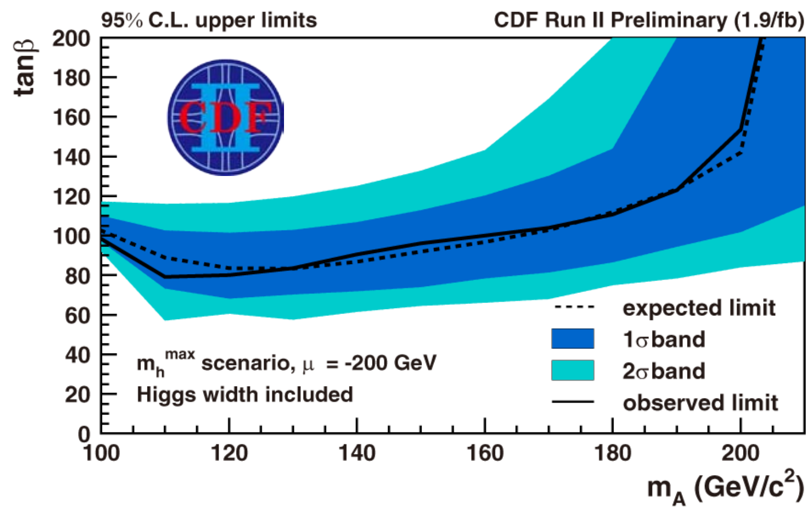
Interpretation to typical MSSM scenario :
Maximal stop mixing
$\mu = -200$GeV

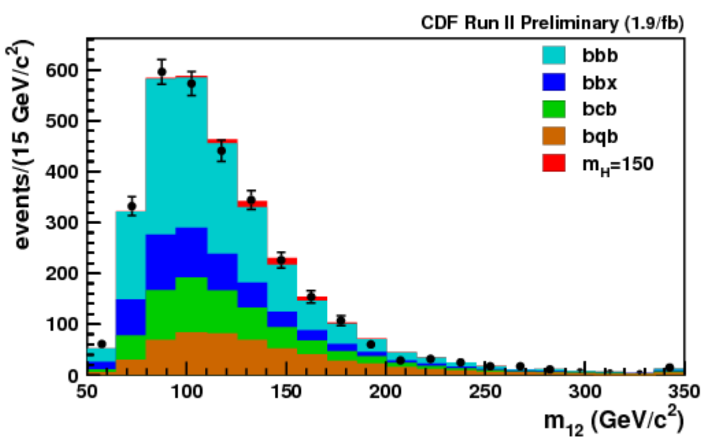
MSSM Neutral Higgs : $\phi b \to bbb$

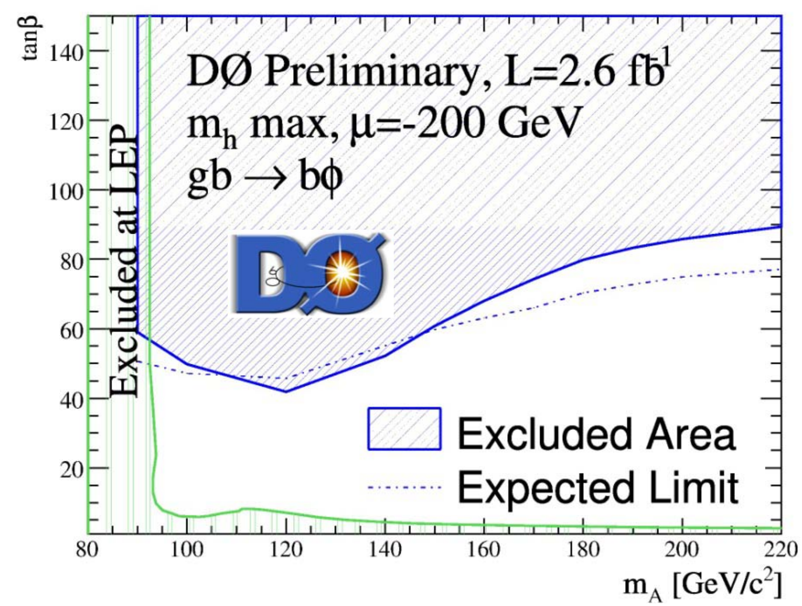
- $gb \to \phi b \to bbb$



- Required 3 b-tagged jets.
- Large multijet background
- Search for peak in dijet mass
  - CDF : 1.9 fb^{-1}, DØ : 2.6 fb^{-1}

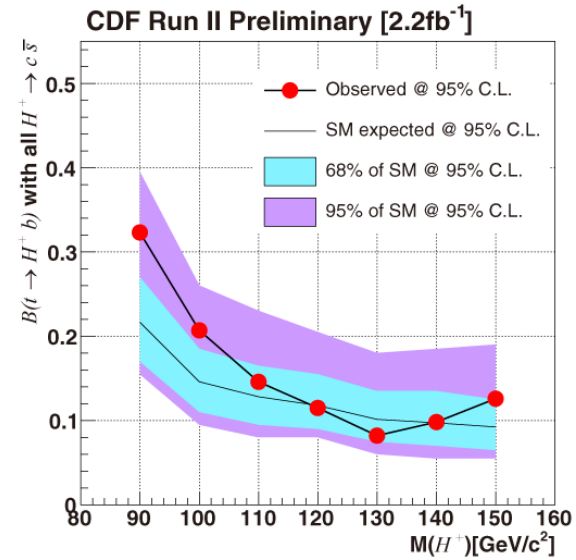


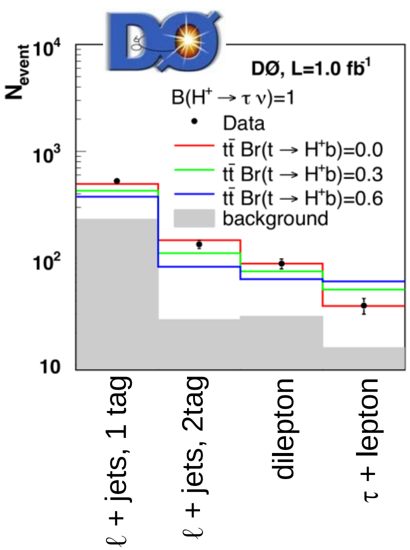


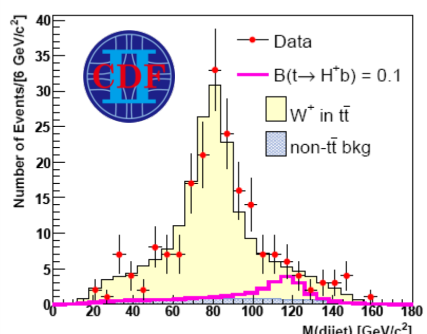


MSSM Charged Higgs

- Search for $H^{\pm}$ in top decays
  - $t \rightarrow H^{\pm}b$
    - $H^{\pm} \rightarrow cs$ (for small $\tan\beta$)
    - $H^{\pm} \rightarrow \tau\nu$ (for large $\tan\beta$)
  - If $H^{\pm}$ exists, there would be deviation from the SM prediction for the final states of tt decay.

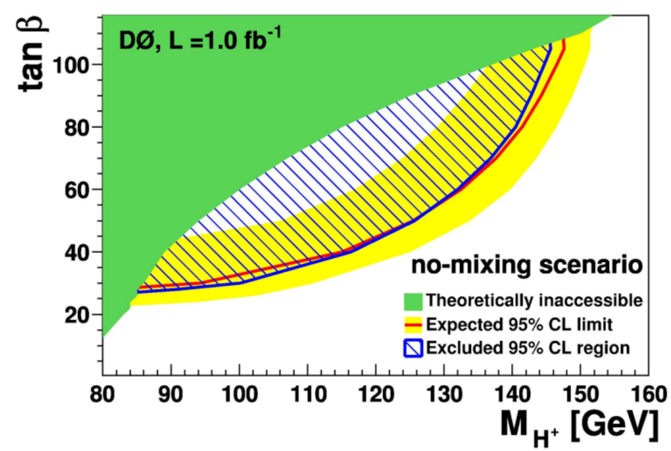






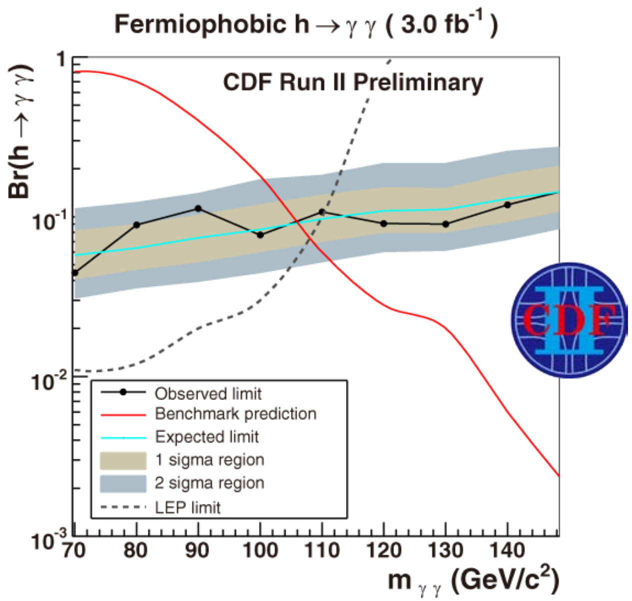
Dijet mass

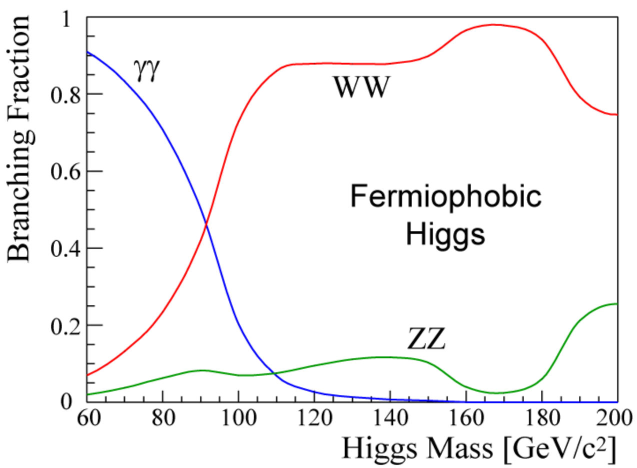
Consistent with SM

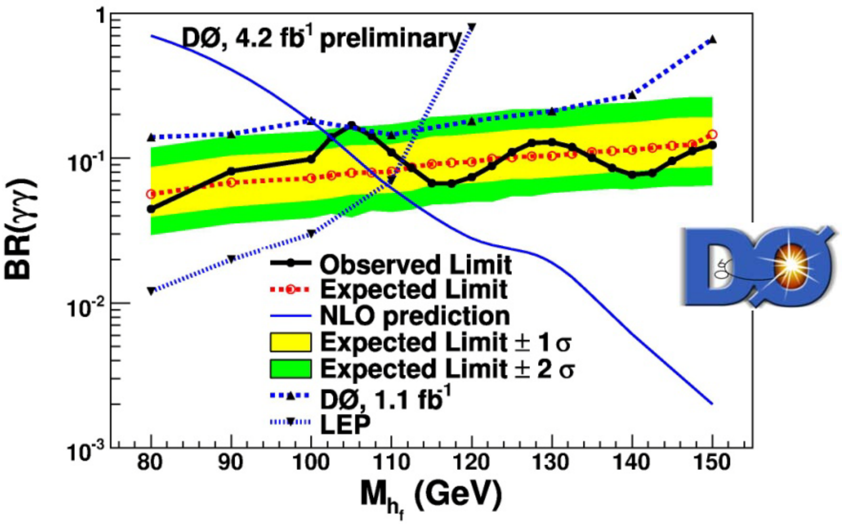


Fermiophobic Higgs

- In some BSM models, Higgs couplings to fermions are suppressed.
  - $\Rightarrow$ Higgs decays to vector bosons are significantly increased.
  - Low mass region : $H \to \gamma\gamma$
  - High mass region : $H \to WW/ZZ$
- Benchmark scenario
  - No fermion couplings and SM couplings to vector boson



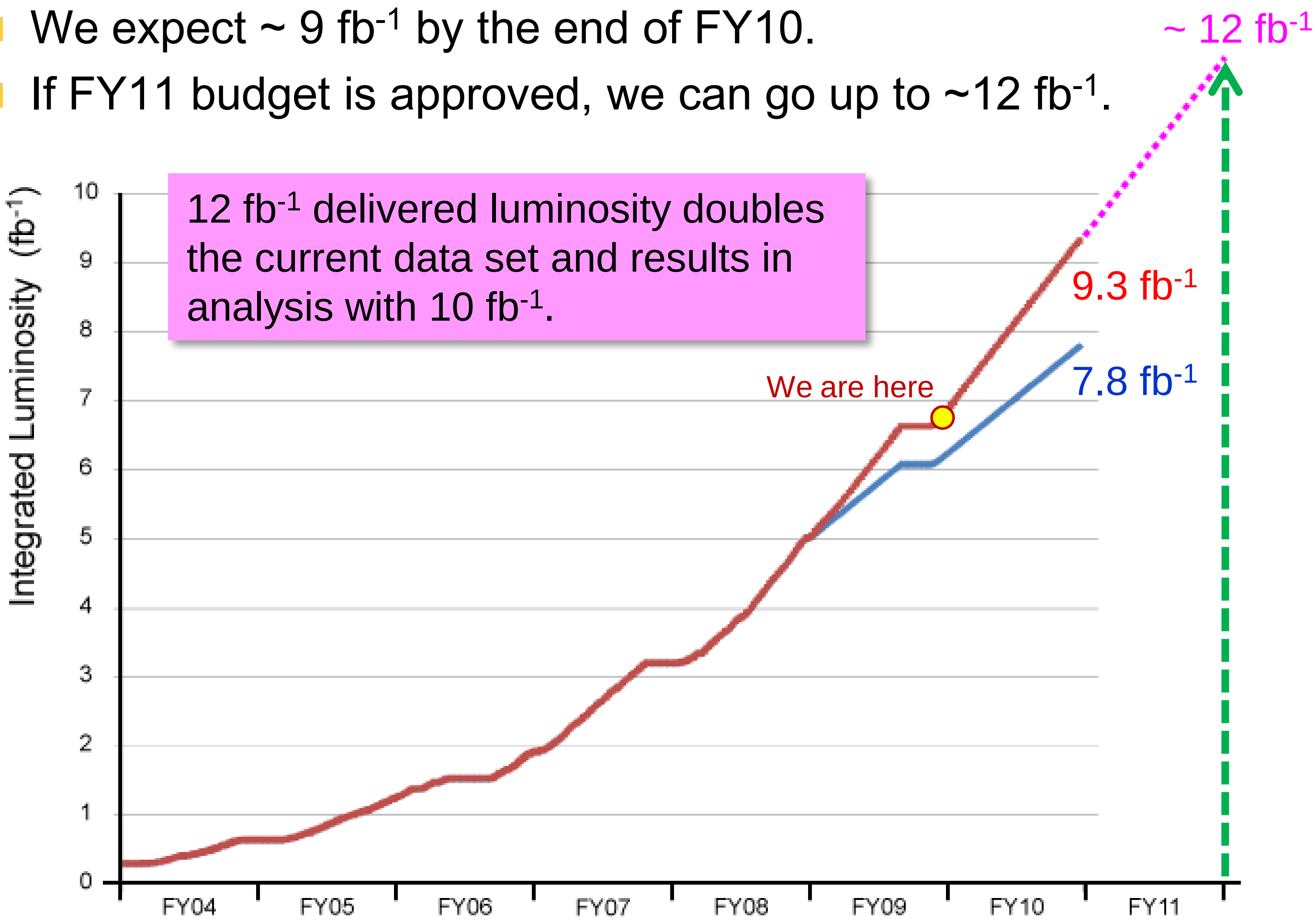




Future Prospects

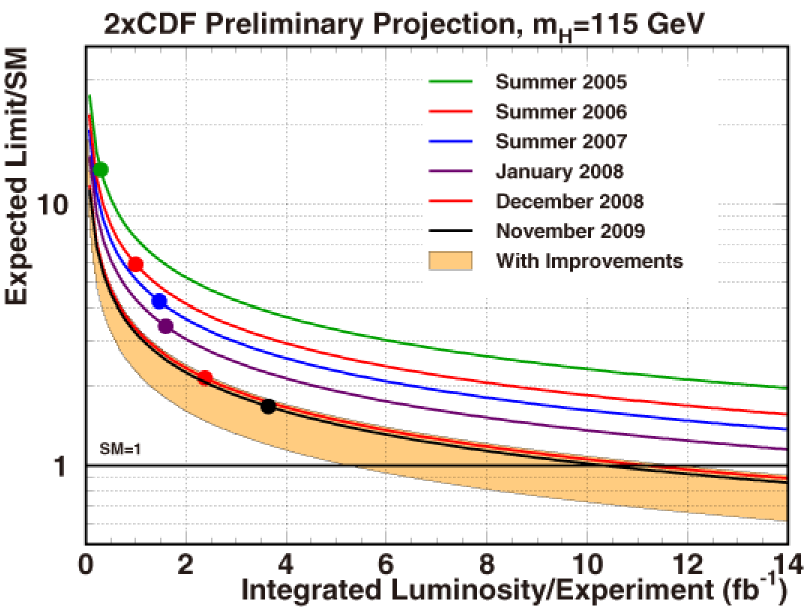
Luminosity Prospects

- Tevatron performance and projection
  - We expect ~ 9 fb^{-1} by the end of FY10.
  - If FY11 budget is approved, we can go up to ~12 fb^{-1}.

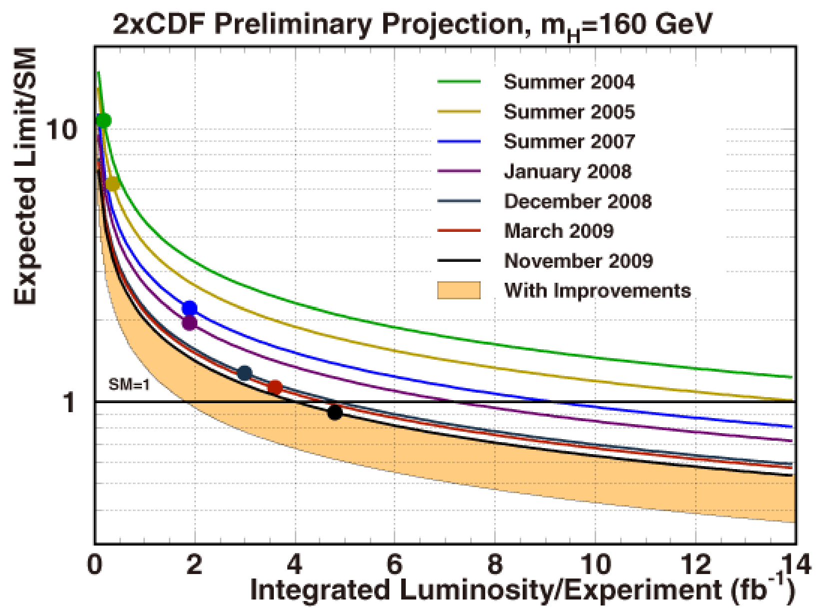


SM Higgs Sensitivity Prospects

For M_H = 115 GeV/c^2



For M_H = 160 GeV/c^2



- Analysis improvements help the sensitivity increase better than 1/sqrt($\mathcal{L}$).
  - Expect to reach 115GeV Higgs with 6~10 fb^{-1}

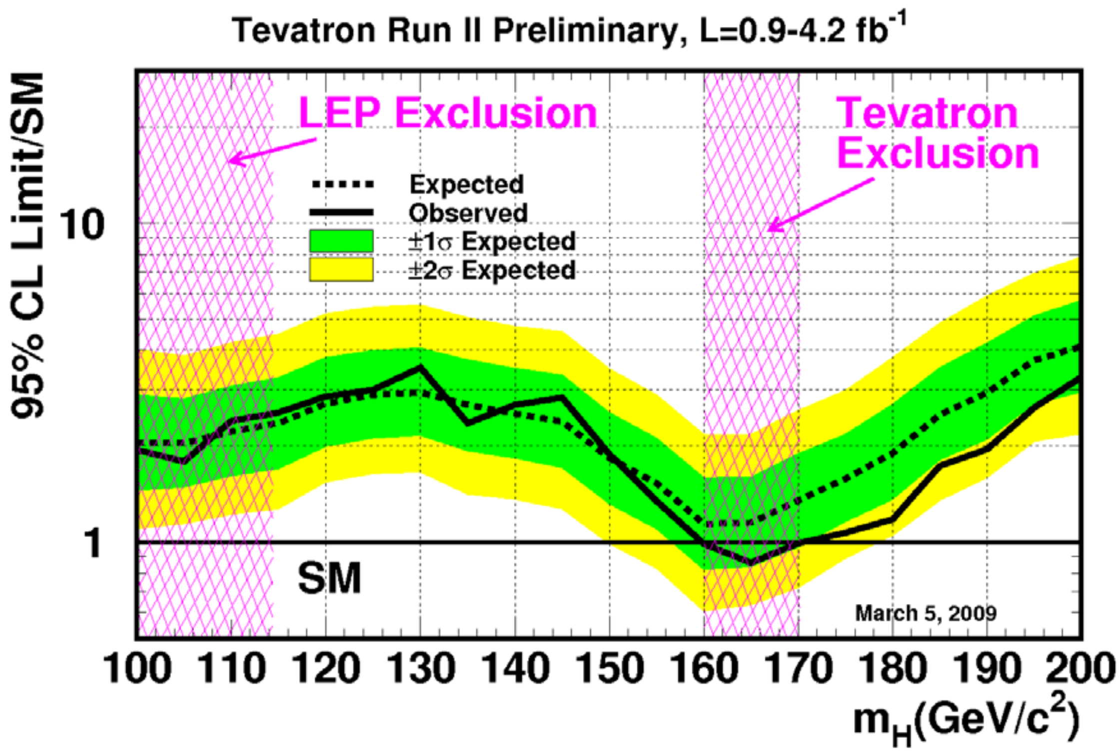
Conclusions

- Tevatron and the collider detectors (CDF and DØ) are performing very well.
  - Delivered 7.4 fb^{-1}, Acquired 6.1 fb^{-1}, Analyzed 5.4 fb^{-1}
  - Expect ~ 9 fb^{-1} by the end of FY10
  - ➢ We all thank accelerator people for excellent beam !

- Higgs searches are in progress in various production and decay channels.
  - SM Higgs Boson :
    - Observed (expected) limit at M_H = 115GeV/c^2 : 2.70 (1.78) $\times\ \sigma_{SM}$
    - Tevatron expects to exclude 159 – 168 GeV/c^2 at 95% C.L.
      Excluded mass range : 163 – 166 GeV/c^2
  - Higgs Bosons Beyond the SM :
    - No sign of discovery yet. But sensitivity is increasing steadily.
  - Increasing luminosity, analysis improvements, … We can go further !

Backup Slides

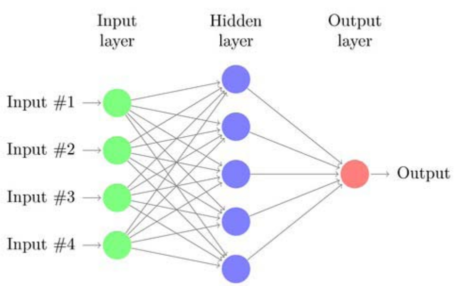
Spring 2009 Result



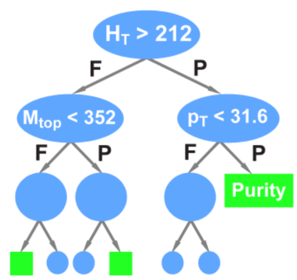
Multivariate Techniques

- Both experiments use advanced multivariate techniques, which combine information from kinematical, topological and particle identification variables, to enhance the signal/background discrimination.

Artificial Neural Networks (NN)



Boosted Decision Trees (BDT)



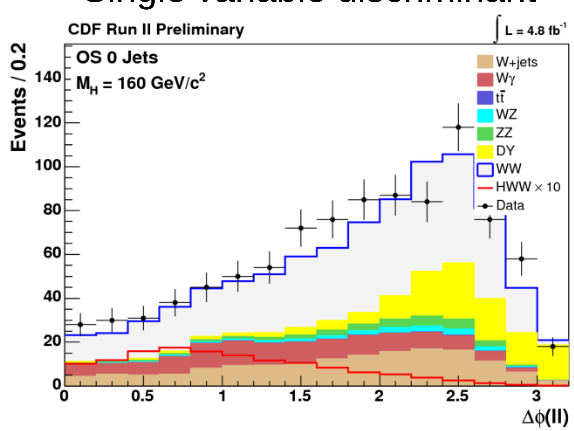
Matrix Element (ME)

Calculating event probability integrating the LO matrix elements

$$d\sigma(\vec{x}) = \sum_{i,j} \int d\vec{y} \left[f_i(q_1, Q^2)dq_1 \times f_j(q_2, Q^2)dq_2 \times \frac{\partial \sigma_{hs,ij}(\vec{y})}{\partial \vec{y}} \times W(\vec{x}, \vec{y}) \times \Theta_{parton}(\vec{y}) \right]$$

p.d.f
ME
Detector response (Transfer function)
Parton level cut

Single variable discriminant



Neural network output