Searches for Low Mass Higgs Boson at the Tevatron

Song-Ming Wang
Academia Sinica

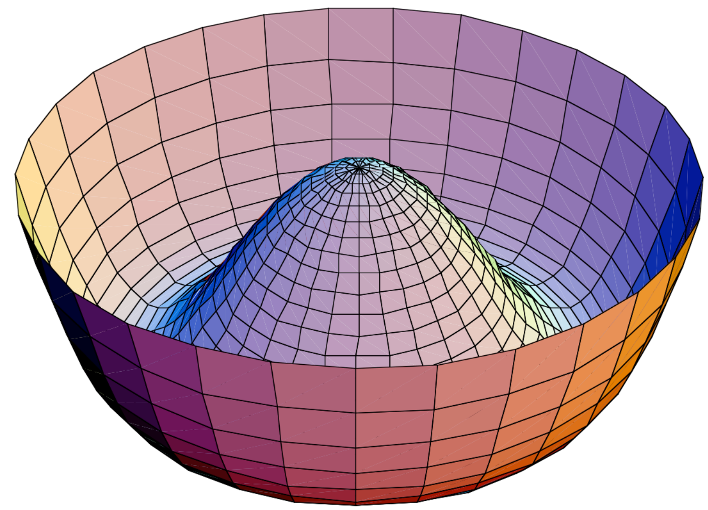
On behalf of the CDF and DØ Collaborations

Les Rencontres de Physique
de la Vallée d'Aoste
La Thuile, Aosta Valley, Italy
2010

Outline

- Introduction
    - Why Higgs ?
- Higgs Production at Tevatron
- Low Mass Higgs Search Strategy
- Results from Various Low Mass Searches
- Prospects
- Summary

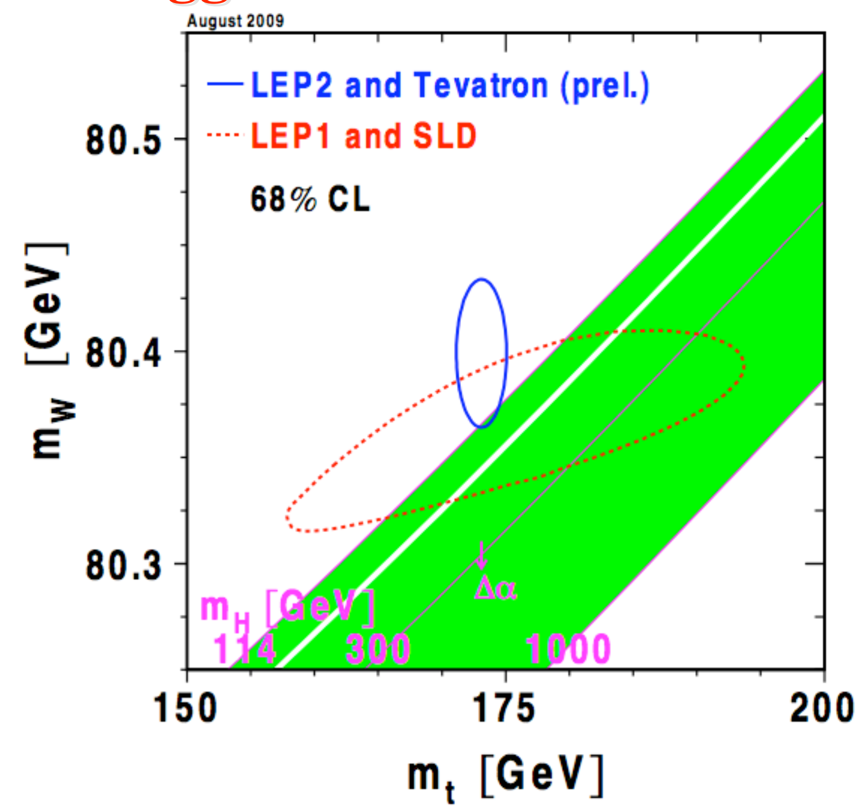
Why Look for a Higgs Boson ?

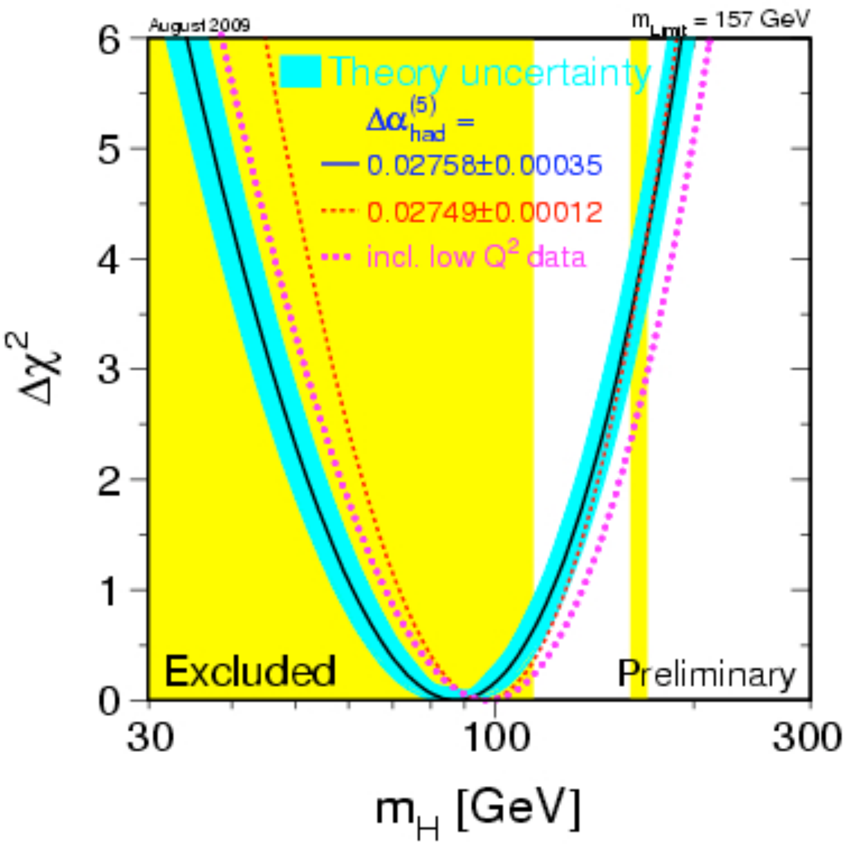


- In Standard Model (SM), Electromagnetism and Weak interactions are unified under the SU(2)xU(1) gauge symmetry
- However the symmetry in the theory has to be broken, otherwise :
  - All particles will be massless
- In SM, the Electro-Weak symmetry is broken via the Higgs mechanism
  - Every particle obtain mass by interacting with Higgs field through exchange of Higgs boson
  - SM predicts existence of a Higgs boson but its mass is not predicted
- Higgs boson is the only undiscovered particle in SM, making its discovery one of the most important present goal in Particle Physics

What We know of the SM Higgs Boson

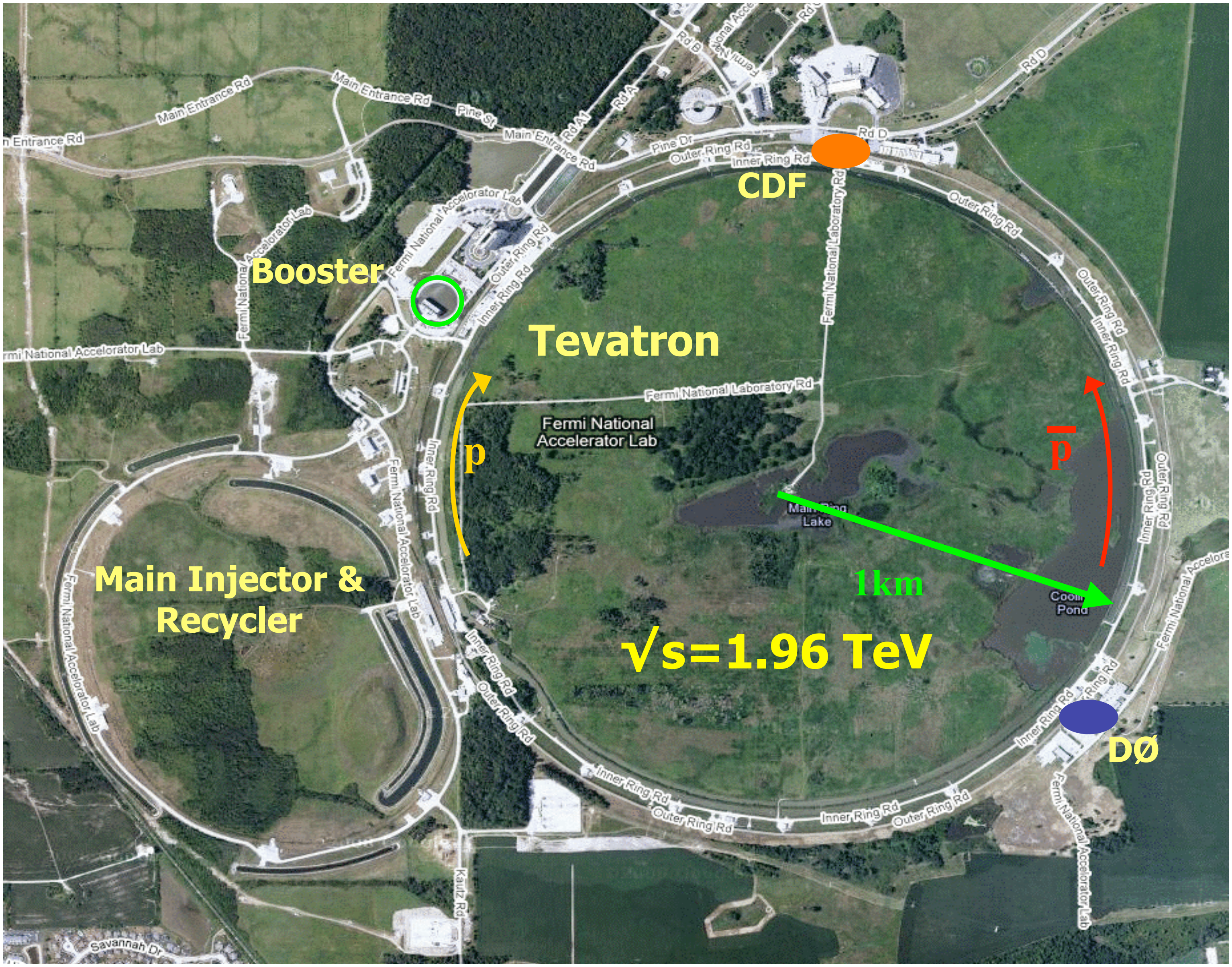
- Lower bound from direct searches at LEP:
  - $m_H > 114$ GeV/c^2
- Top and W mass measurements are constraining the Higgs sector



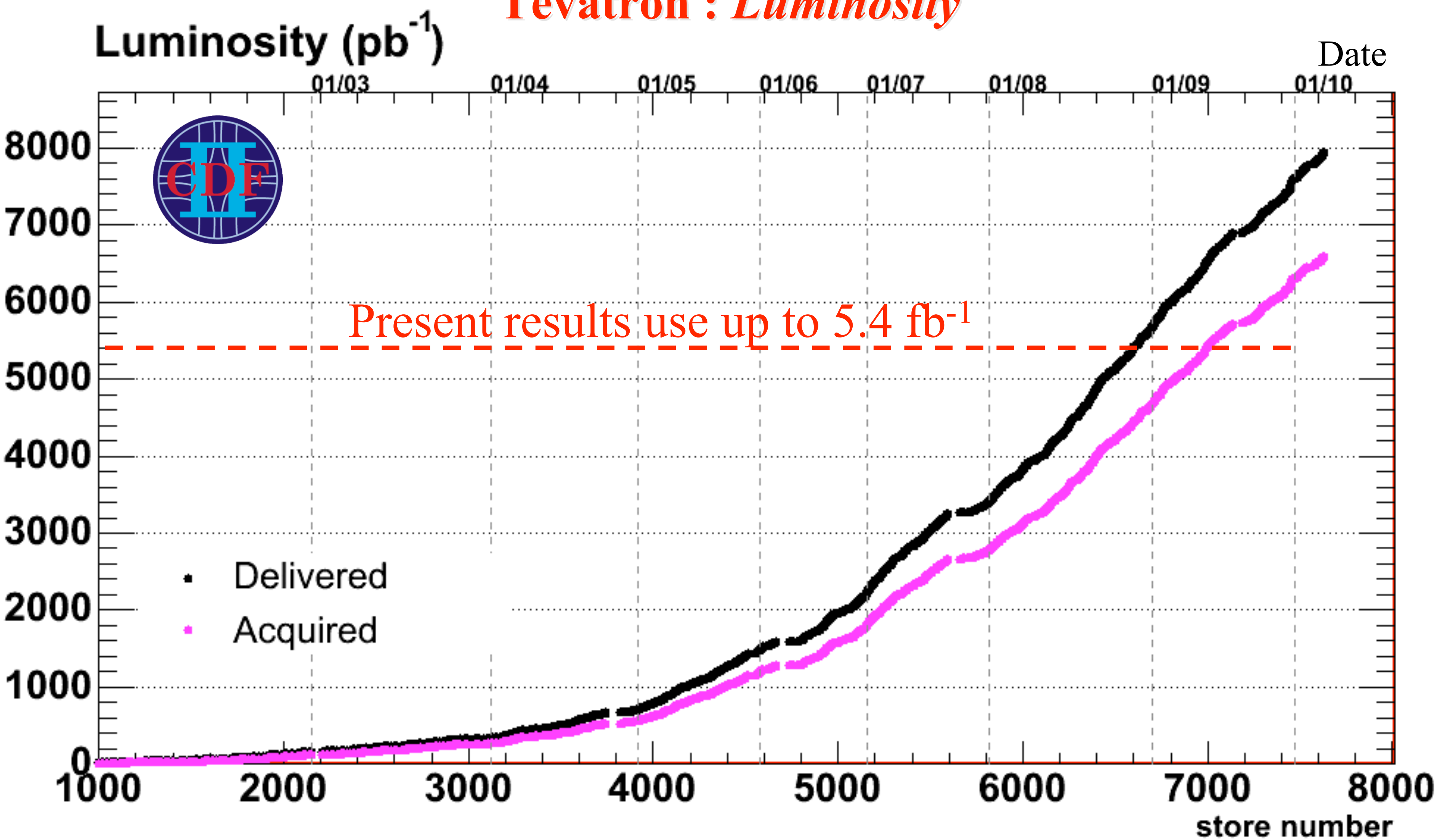


- Latest (LEPEWWG Aug '09) fits to precision Electroweak data
  - $m_H = 87^{+35}_{-26}$ GeV/c^2
  - $m_H < 157$ GeV/c^2 (@ 95% CL)
  - $m_H < 186$ GeV/c^2 (include LEP limit)

Tevatron : *Most Powerful p-pbar Collider !*



Tevatron : *Luminosity*

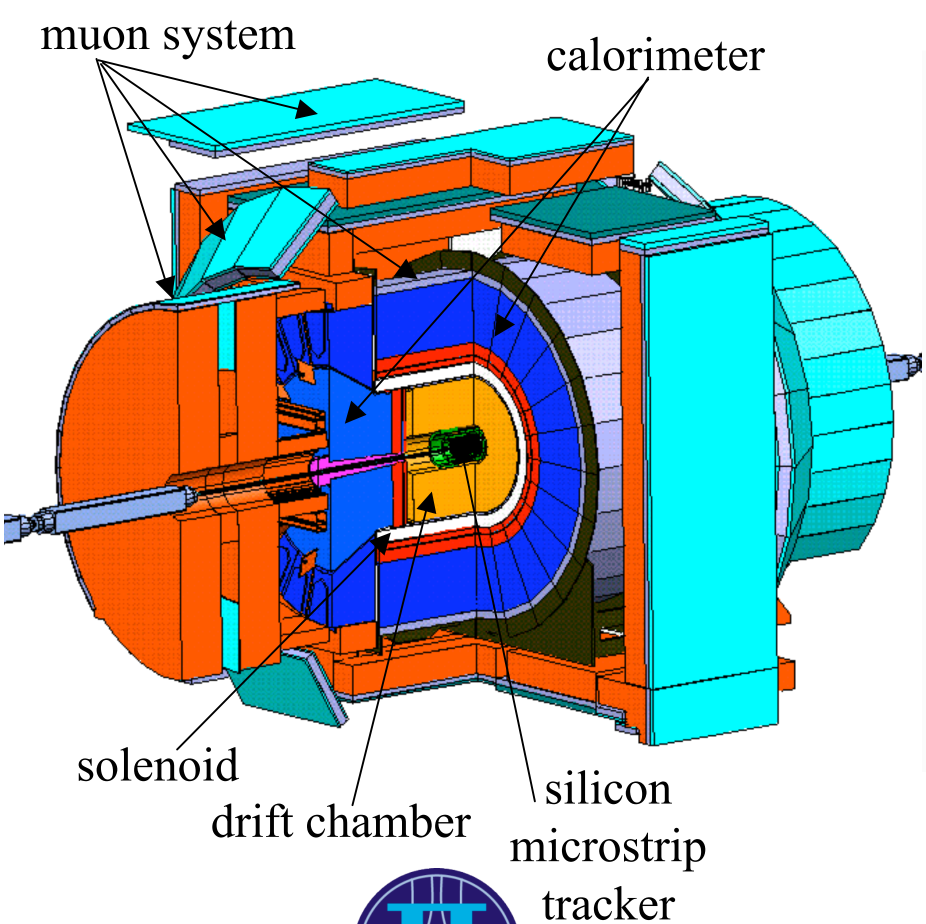


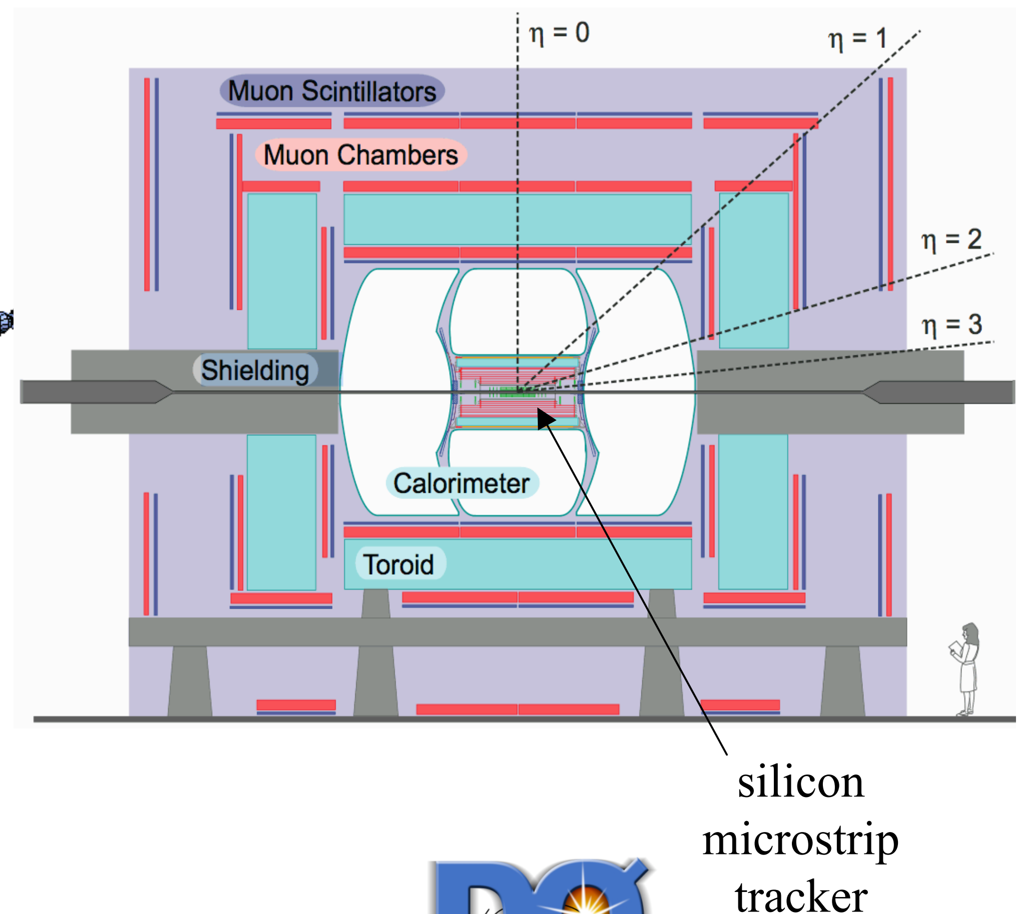
- Since start of Run 2 delivered ~8 fb^{-1} per experiment
  - CDF/D0 : ~6.6-7 fb^{-1}
- Expected to deliver ~10-12 fb^{-1} by end of 2011

The Tevatron Experiments

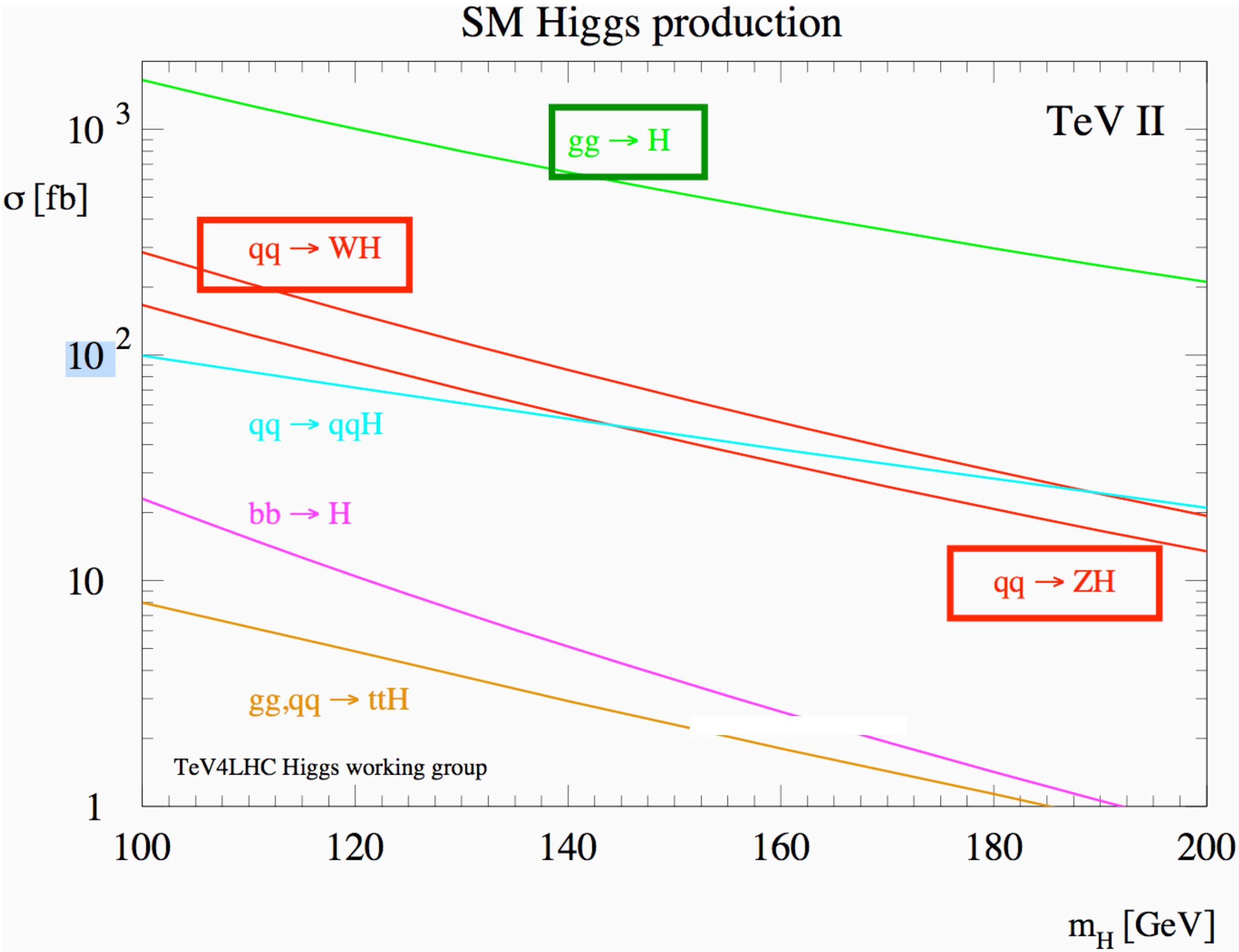
Multipurpose detectors :

- Electron, muon, tau identification
- Jet and missing energy measurement
- Heavy-flavor tagging through displaced vertices and soft leptons

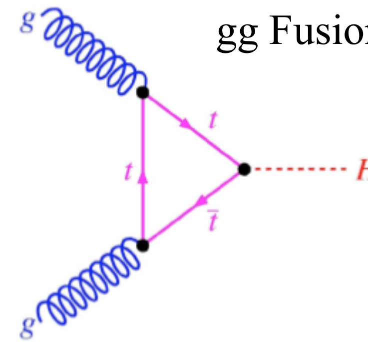




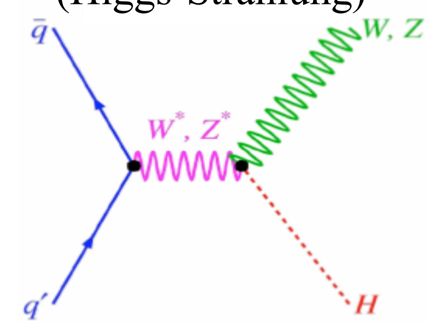
Higgs Boson Production at the Tevatron



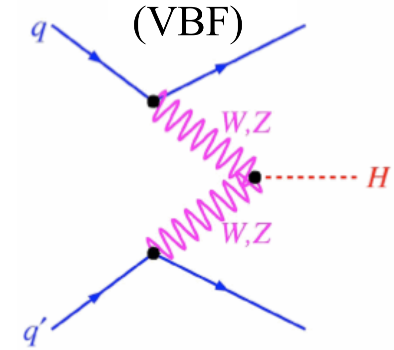
gg Fusion



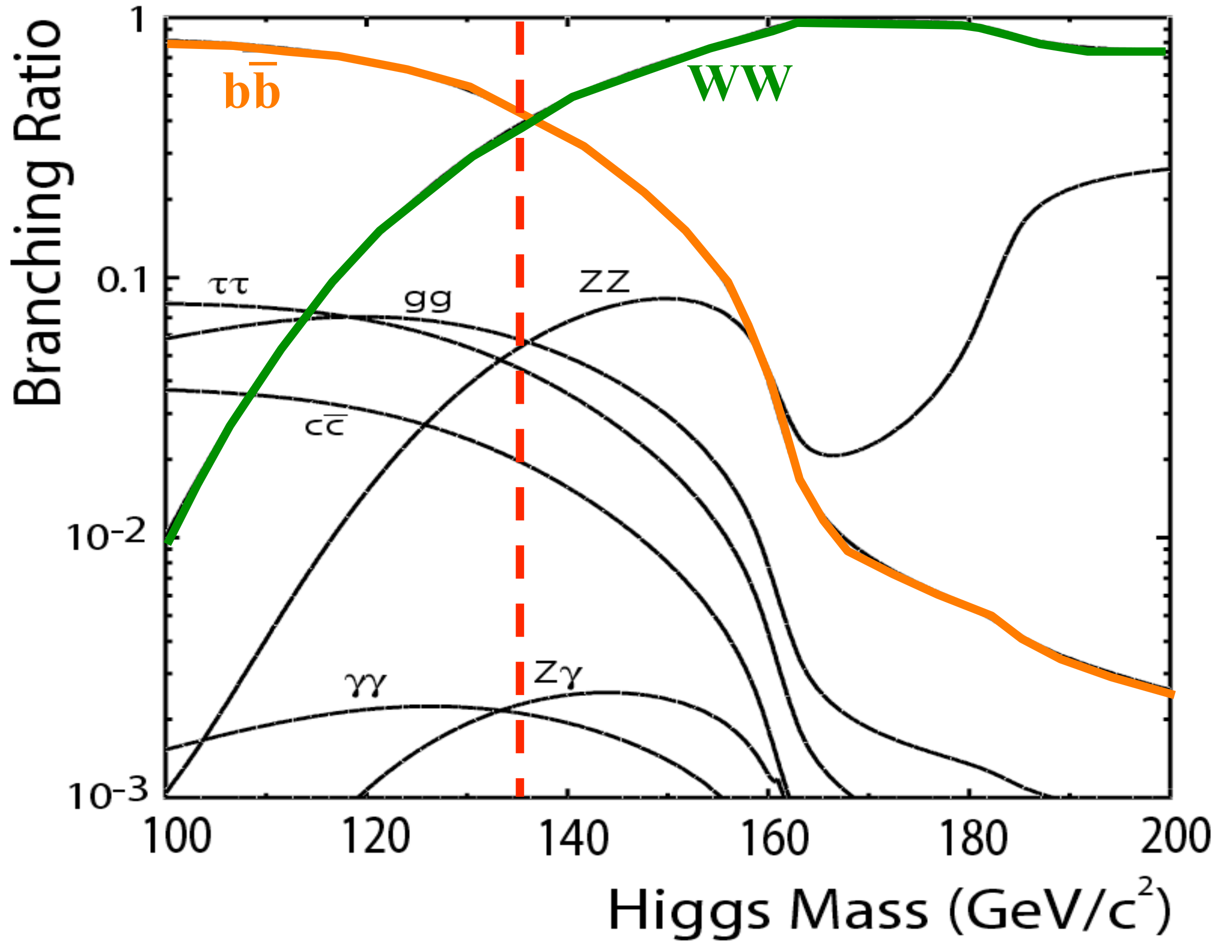
Associated
(Higgs-Strahlung)



Vector Boson Fusion
(VBF)



SM Higgs Decay

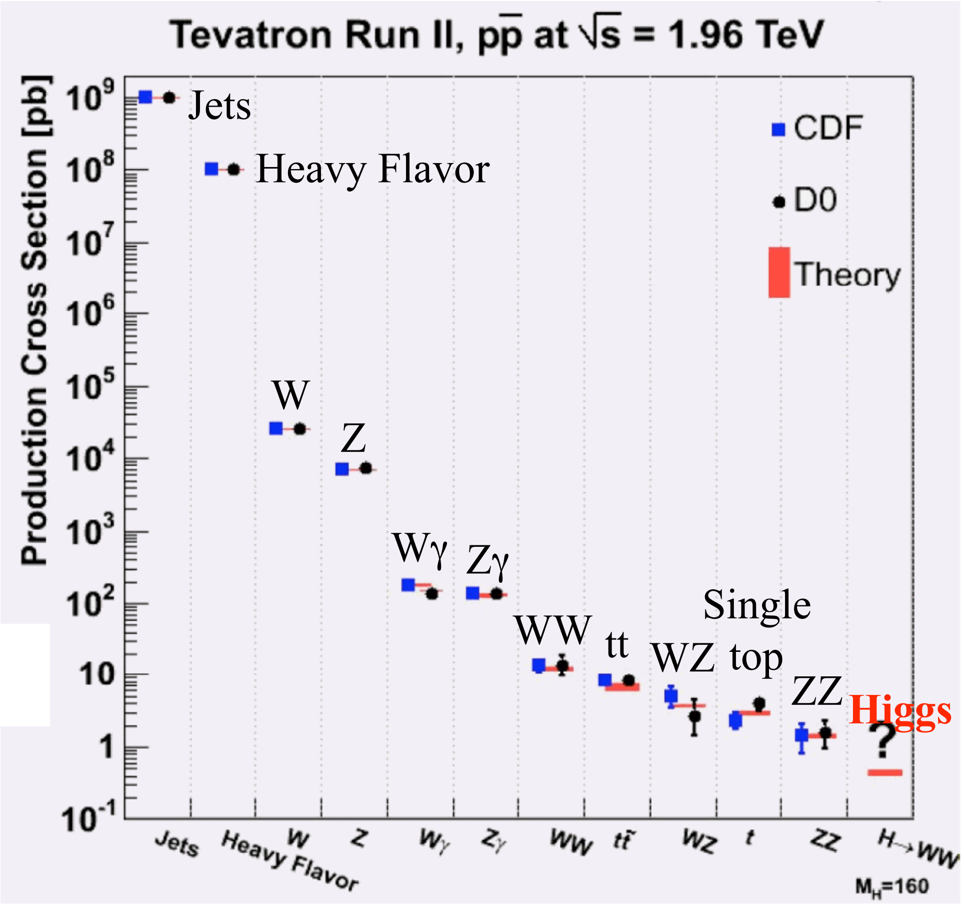


• Higgs decays predominantly :

- $H \rightarrow b\bar{b}$ (m_H<135 GeV)
- $H \rightarrow W^+W^-$ (m_H>135 GeV)

Higgs Search Strategy

- At Tevatron, Higgs production is very rare process
- Difficult to search, but not impossible. CDF/DØ already probing processes with σ~1 pb (WZ, ZZ, single top).
- **Search Strategy:**
  - Identify Higgs signal by its unique final state signature
  - Increase signal acceptance
  - Advanced discriminating algorithms
  - Search in as many channels as possible *(will present results from various channels)*

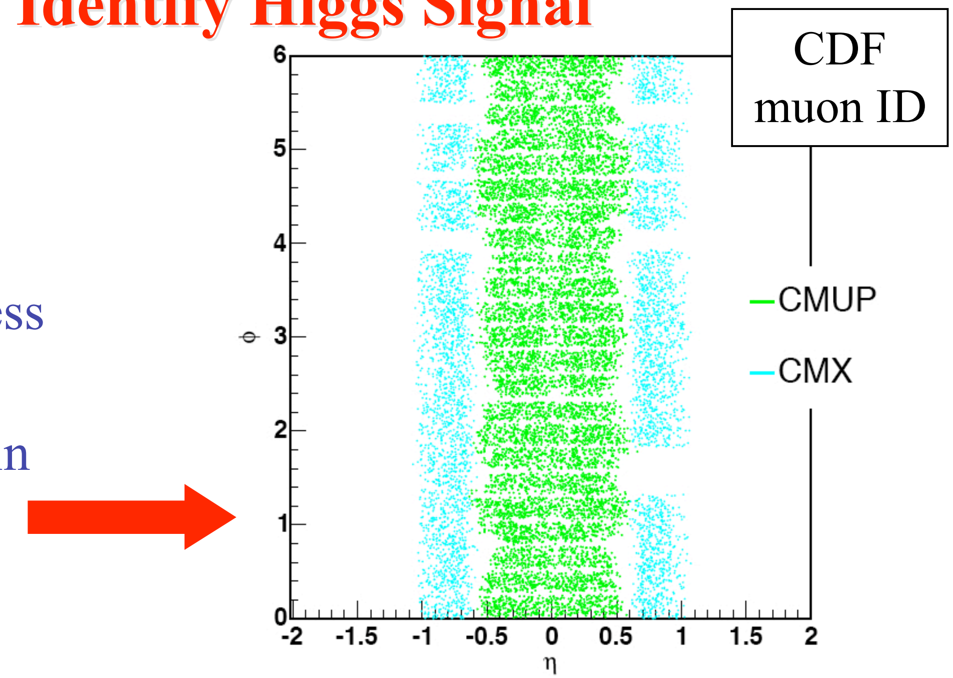


Analysis Techniques : Identify Higgs Signal

•Look for distinctive signature in final state

High Pt Leptons:

- WH→$l\nu$bb, ZH→llbb (l : e,μ,τ)
- Identify charged leptons can greatly suppress multi-jet background
- Extend lepton coverage, using leptons not in detector fiducial region, in forward region

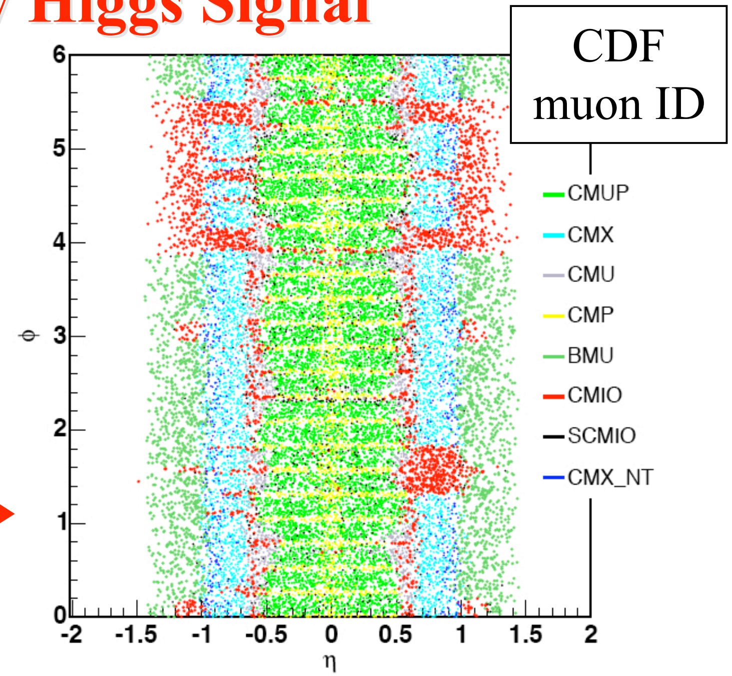


Analysis Techniques : Identify Higgs Signal

•Look for distinctive signature in final state

High Pt Leptons:

- WH→$l\nu$bb, ZH→llbb (l : e,μ,τ)
- Identify charged leptons can greatly suppress multi-jet background
- Extend lepton coverage, using leptons not in detector fiducial region, in forward region

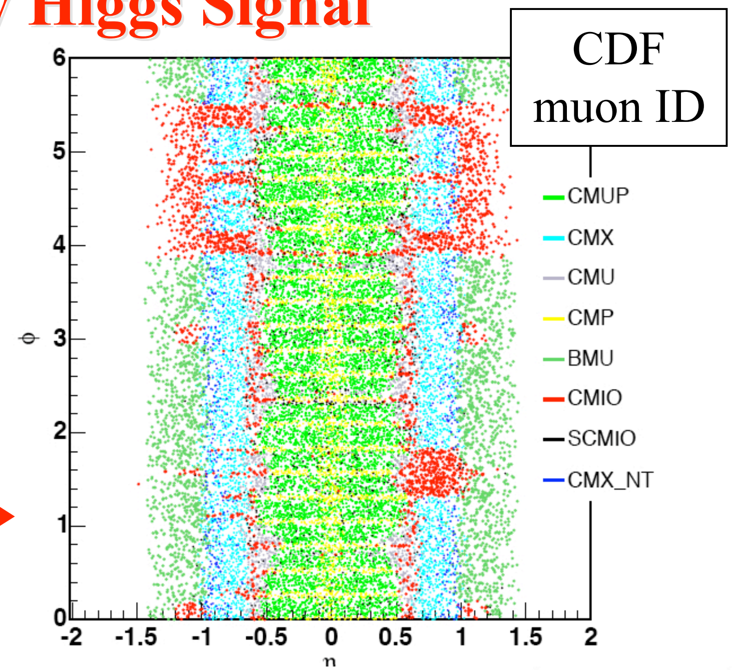


Analysis Techniques : Identify Higgs Signal

•Look for distinctive signature in final state

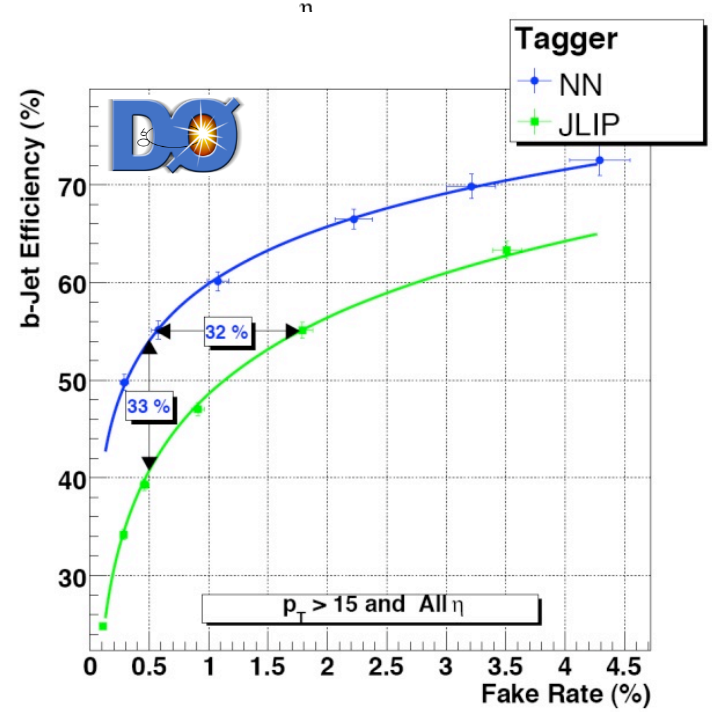
High Pt Leptons:

- WH→$l\nu$bb, ZH→llbb (l : e,μ,τ)
- Identify charged leptons can greatly suppress multi-jet background
- Extend lepton coverage, using leptons not in detector fiducial region, in forward region



Heavy-Flavor Jets :

- Low mass Higgs decays primarily H→bb
- Tag the b-jets by exploiting long life time of B hadrons
- Develop advanced tagging algorithms, increase tagging efficiency and reduce fakes

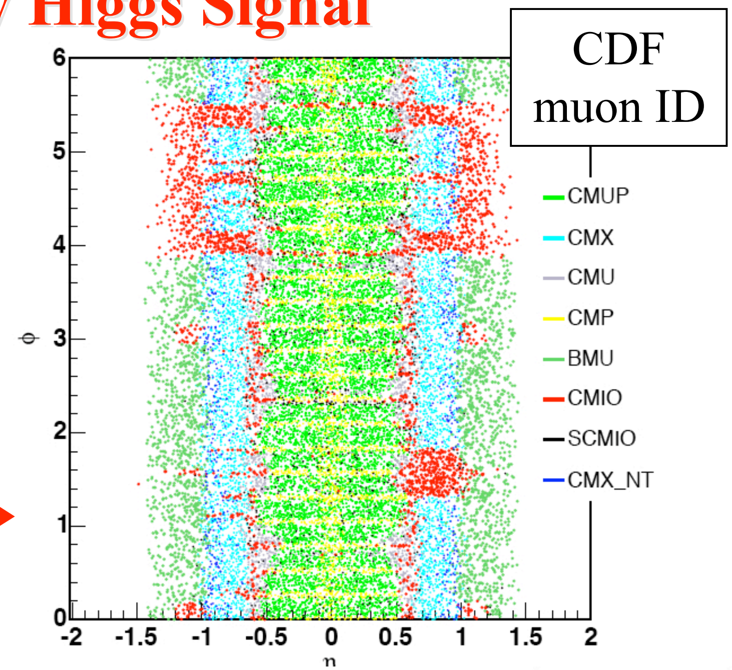


Analysis Techniques : Identify Higgs Signal

•Look for distinctive signature in final state

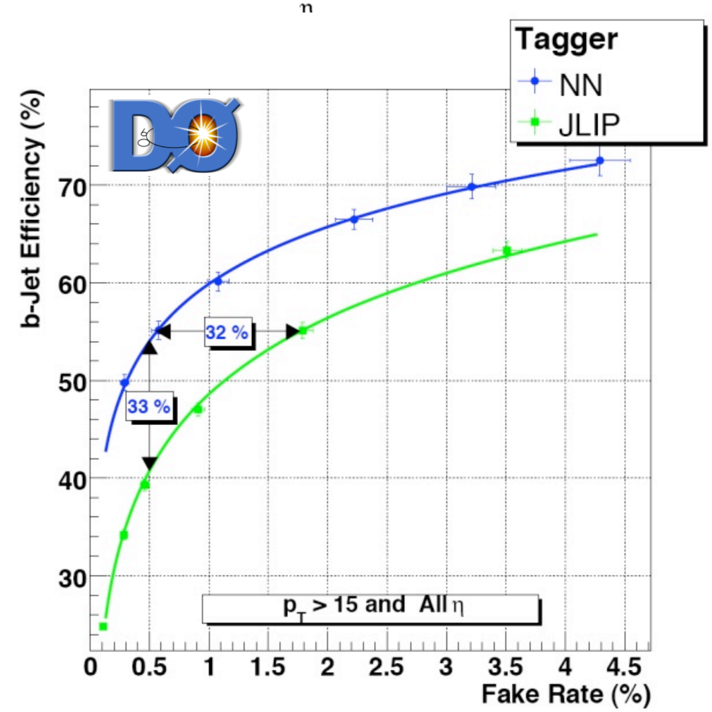
High Pt Leptons:

- WH→$l\nu$bb, ZH→llbb (l : e,μ,τ)
- Identify charged leptons can greatly suppress multi-jet background
- Extend lepton coverage, using leptons not in detector fiducial region, in forward region



Heavy-Flavor Jets :

- Low mass Higgs decays primarily H→bb
- Tag the b-jets by exploiting long life time of B hadrons
- Develop advanced tagging algorithms, increase tagging efficiency and reduce fakes

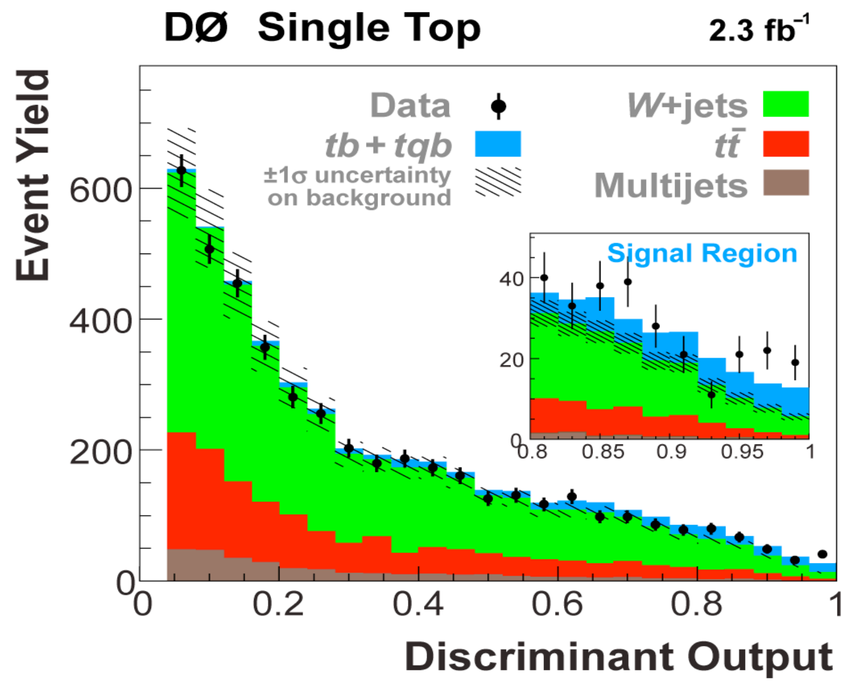


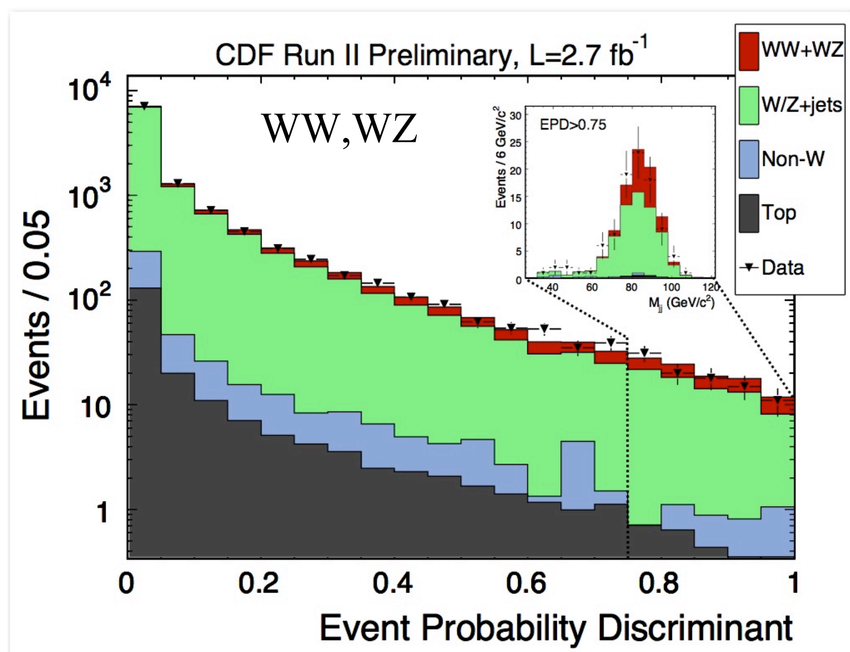
Large Missing E_T (MET):

- ZH→$\nu\nu$bb, WH→$l\nu$bb : MET from ν
- Require large MET can also greatly reduce multi-jet background

Analysis Techniques : Multivariate Discriminant

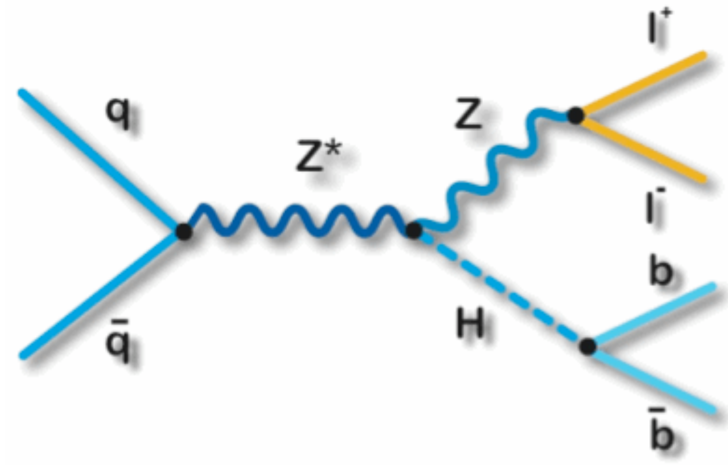
- Expected Higgs signal too small for counting experiment search
- Single kinematic distribution does not provide sufficient discriminating power
- Exploit every possible information in an event
- Multivariate discriminant tools:
  - Artificial Neural Network (NN)
  - Boosted Decision Tree (BDT)
  - Matrix Element (ME) probabilities
- Multivariate tools have been successfully applied to rare processes:
  - Single top
  - WW,WZ (in lvqq final state)



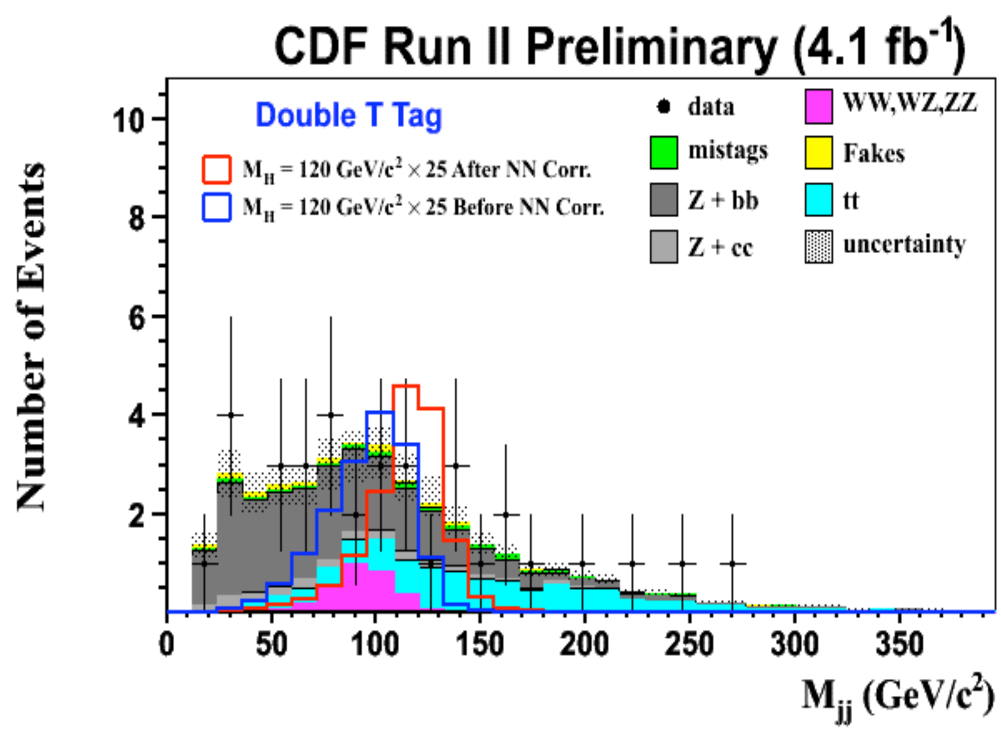


Results from Various Low Mass Searches

$ZH \rightarrow l^+l^-bb$ ($l = e,\mu$)



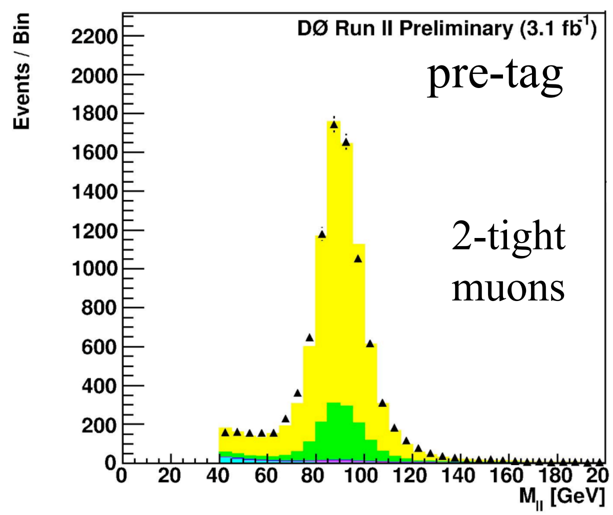
- Low signal statistics, but clean channel
- Fully reconstructible final state, 2 resonances
- Event Selection :
  - Select Z candidate decaying into *ee* or *$\mu\mu$*
  - $\geq$2 jets, with $\geq$1 b-tag jet

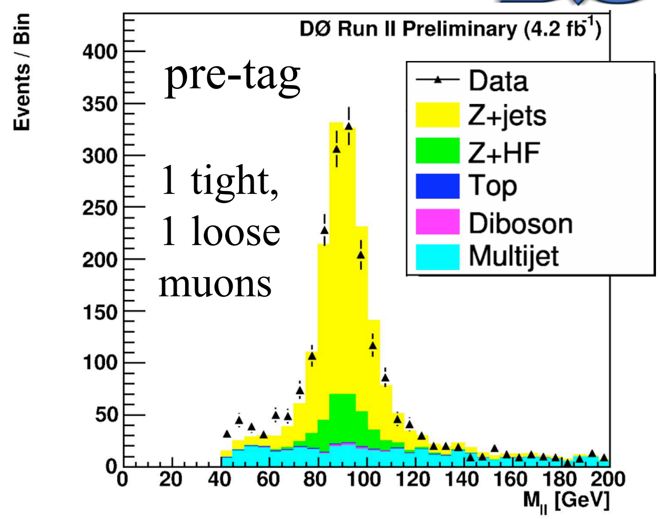


- Jet energy resolution is crucial in constructing M(bb) mass for signal/background separation
- CDF, DØ use event information (e.g. MET, Z mass, vector transverse momentum of Zjj) to correct jets' energy

$ZH \rightarrow l^+l^-bb$ ($l = e,\mu$)

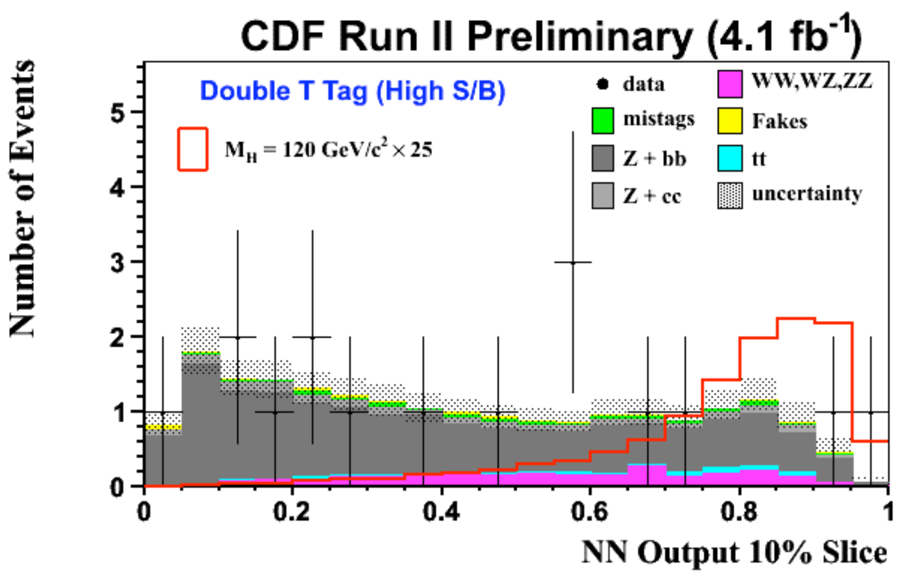
- Search performed in several sub-channels :
  - Tight, loose lepton ID
  - Single, double b-tag jets

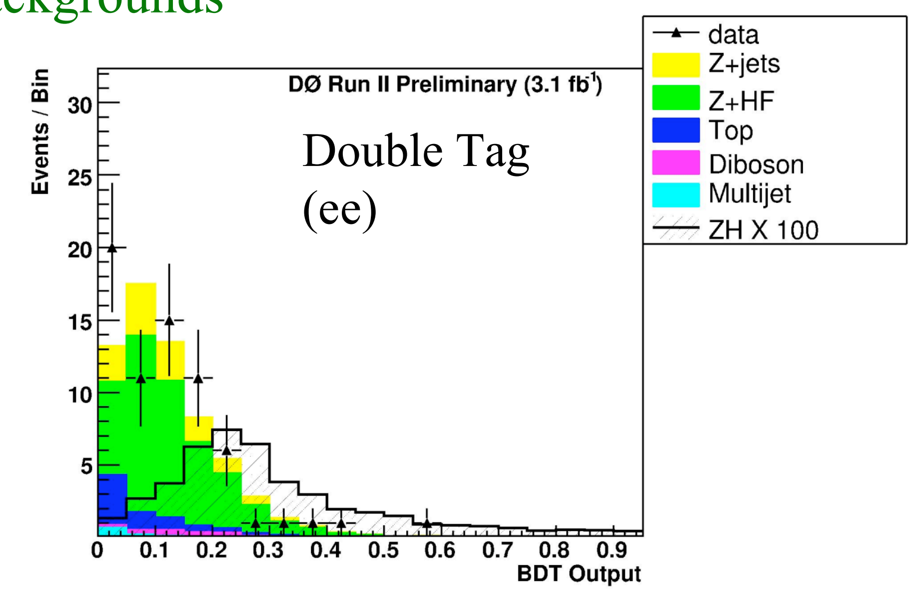




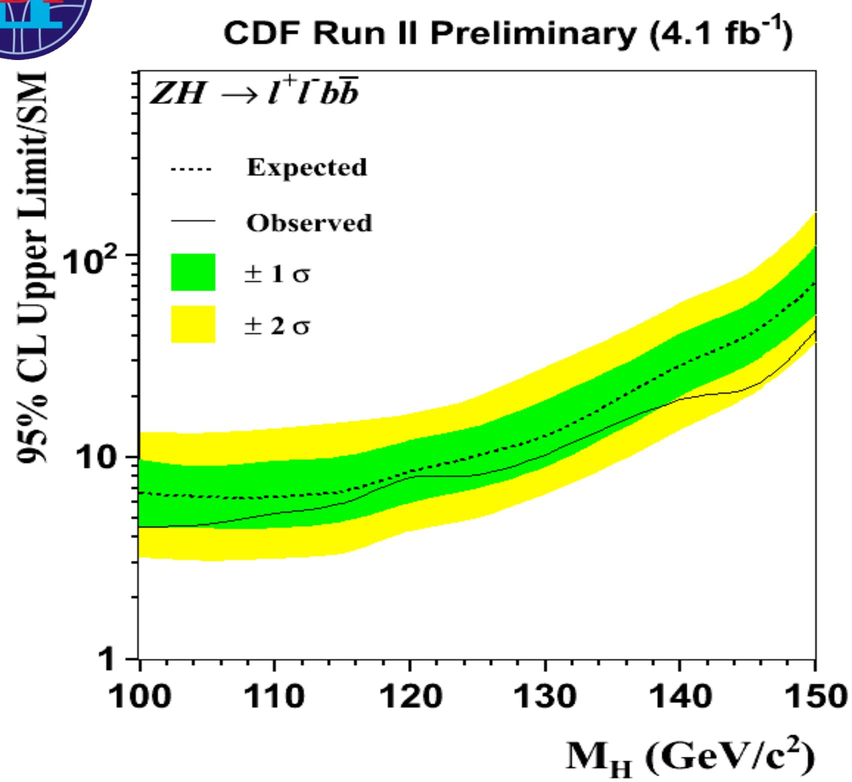
Multivariate algorithms to separate signal from backgrounds:

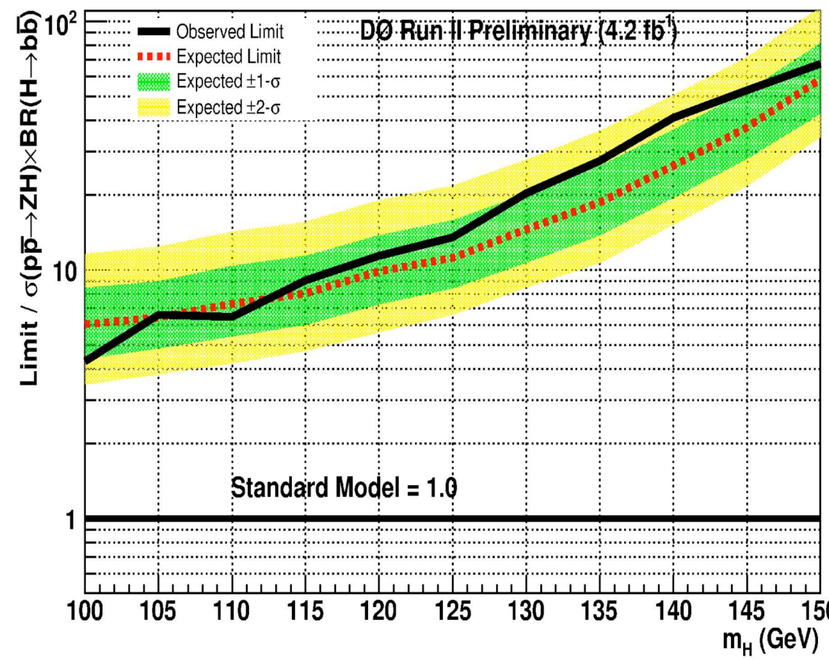
- CDF : 2D NN (separate ZH vs ttbar, ZH vs Z+jets)
- DØ : Train BDT to separate ZH from SM backgrounds





ZH→l⁺l⁻bb (l = *e*,*μ*)

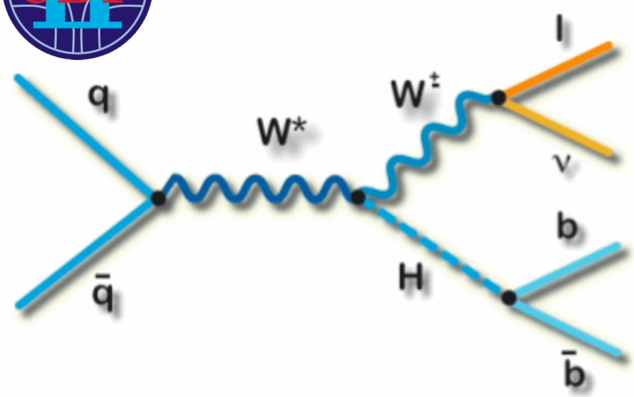




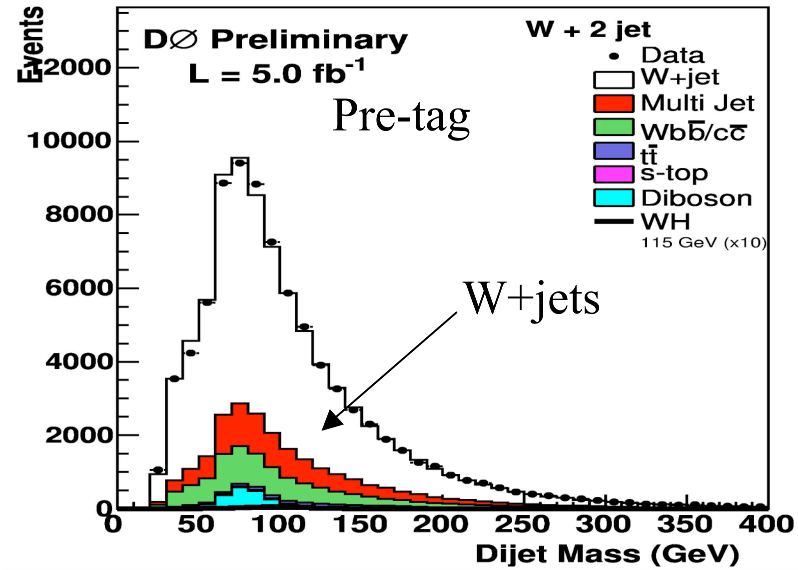
Mass=115 GeV/c^2	∫L (fb^{-1})	Expected Limit	Observed Limit
CDF	4.1	6.8	5.9
DØ	4.2	8.0	9.1

- All limits will be presented as ratios to the SM prediction σ×BR

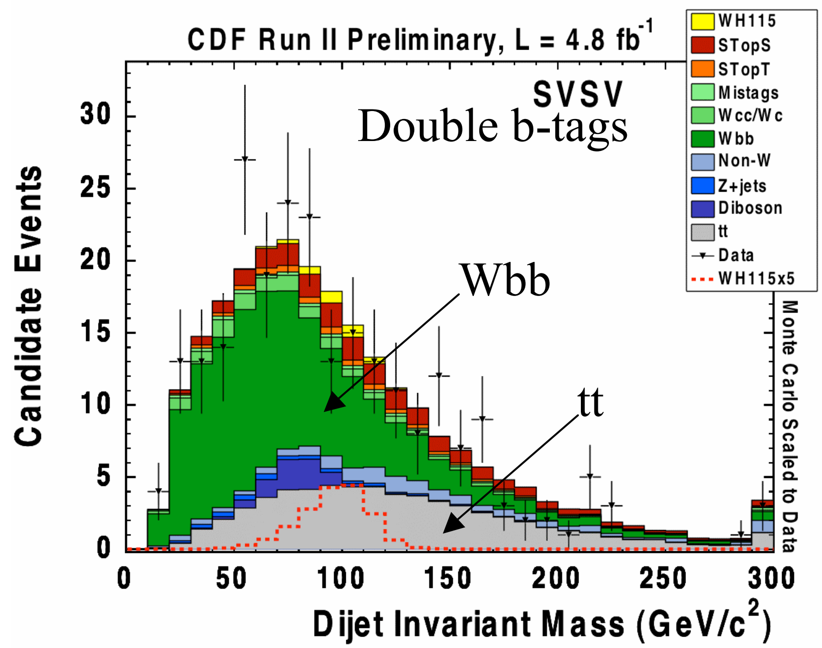
WH→lνbb (l = *e*,*μ*)



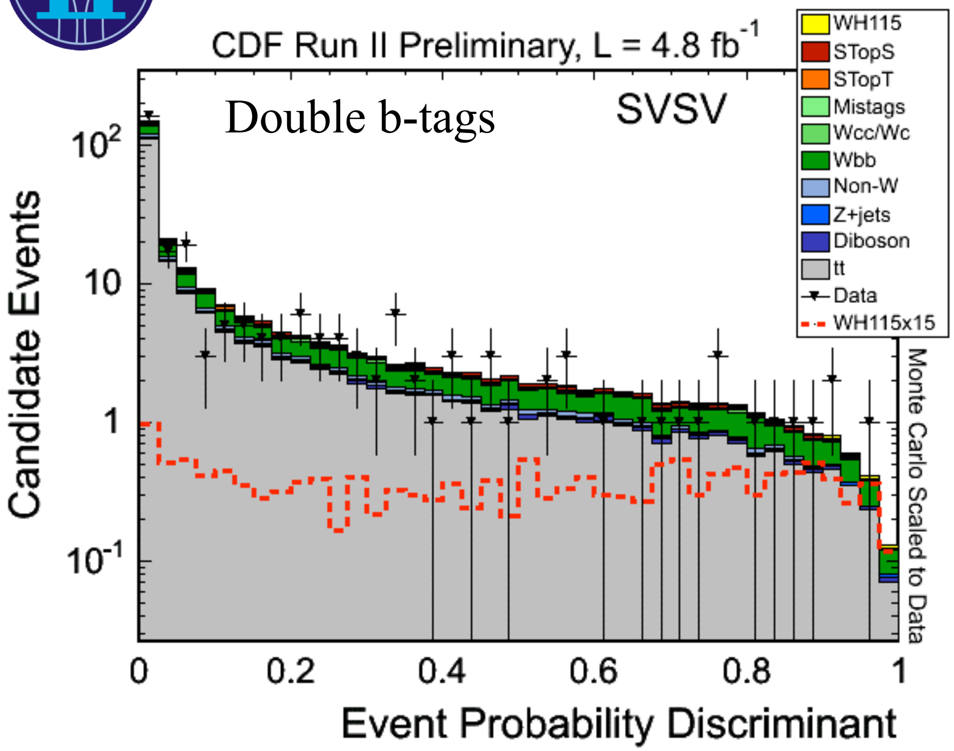
- Clean signature, relatively larger signal statistics

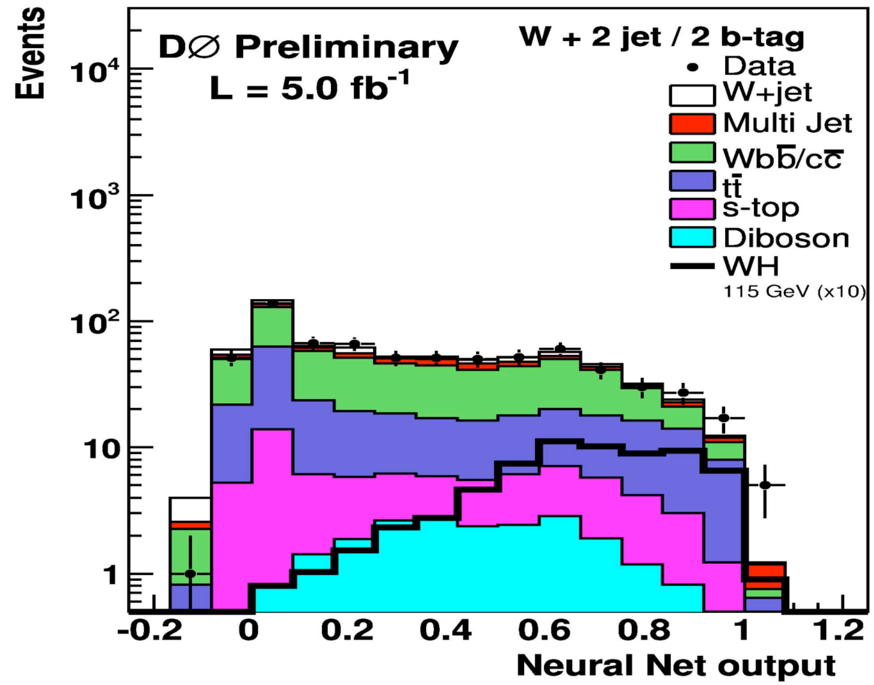


- Event Selection:
  - 1 high Pt *e* or *μ*
  - large missing transverse energy
  - ≥2 jets, ≥1 b-tag jet
- Main backgrounds:
  - W+heavy-flavor jets
  - Mistags (light-flavor jets mis-ID as b-jets)
  - QCD multi-jet (jet faking lepton)
  - Top, Dibosons



$WH \rightarrow l\nu bb$ ($l = e,\mu$)





To improve search sensitivity :

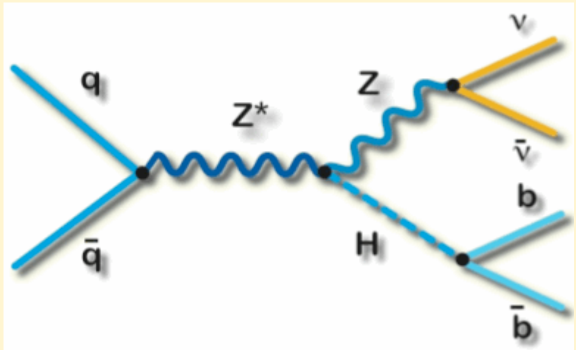
- CDF : use ME method to calculate an Event Probability Discriminant
- DØ : train NN on several kinematic variables to separate signal from background

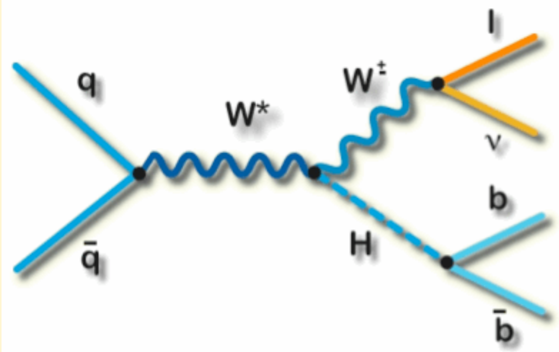
Mass=115 GeV/c^2	$\int L$ (fb^{-1})	Expected Limit	Observed Limit
CDF	4.8	3.8	3.3
DØ	5.0	5.1	6.9

Missing Transverse Energy + Jets Final State

- Contributions from:
  - $ZH \to \nu\nu bb$
  - $WH \to l\nu bb$

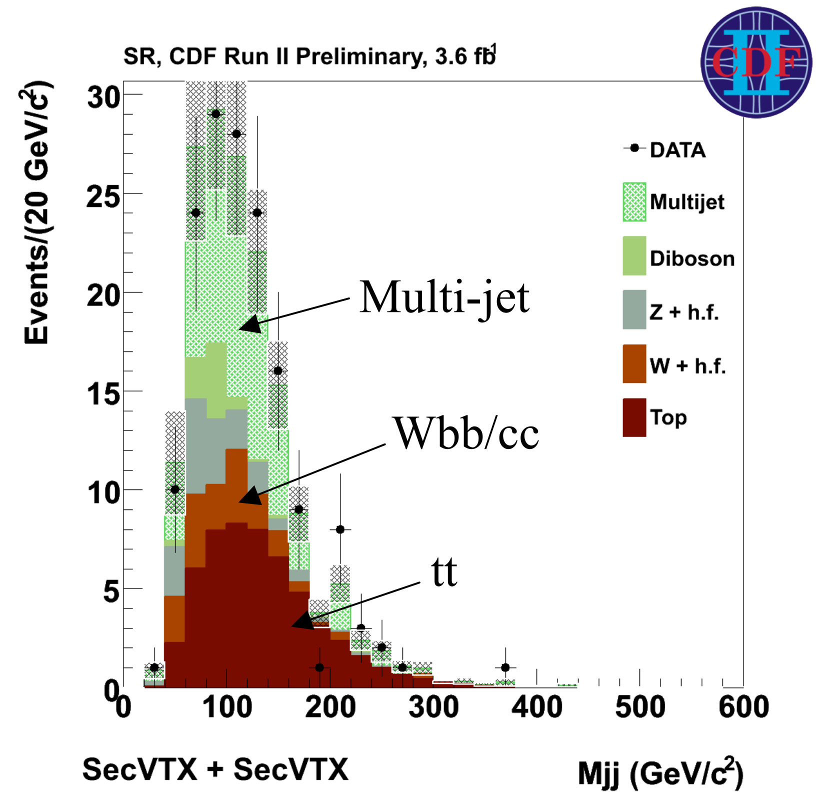
  } l not identified, or identified as hadronic tau





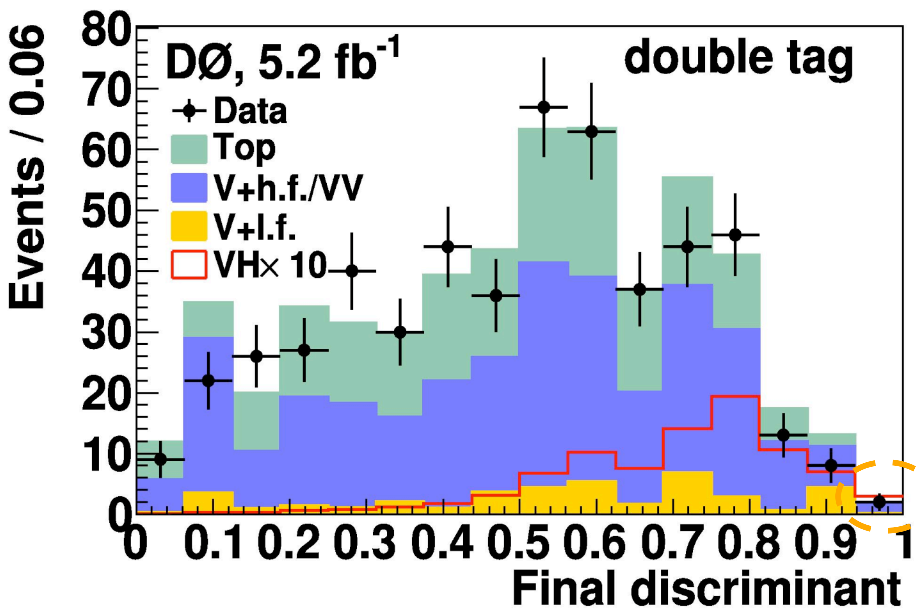
- Signature : large MET + heavy-flavor jets
- Large signal statistics but large background from multi-jet processes

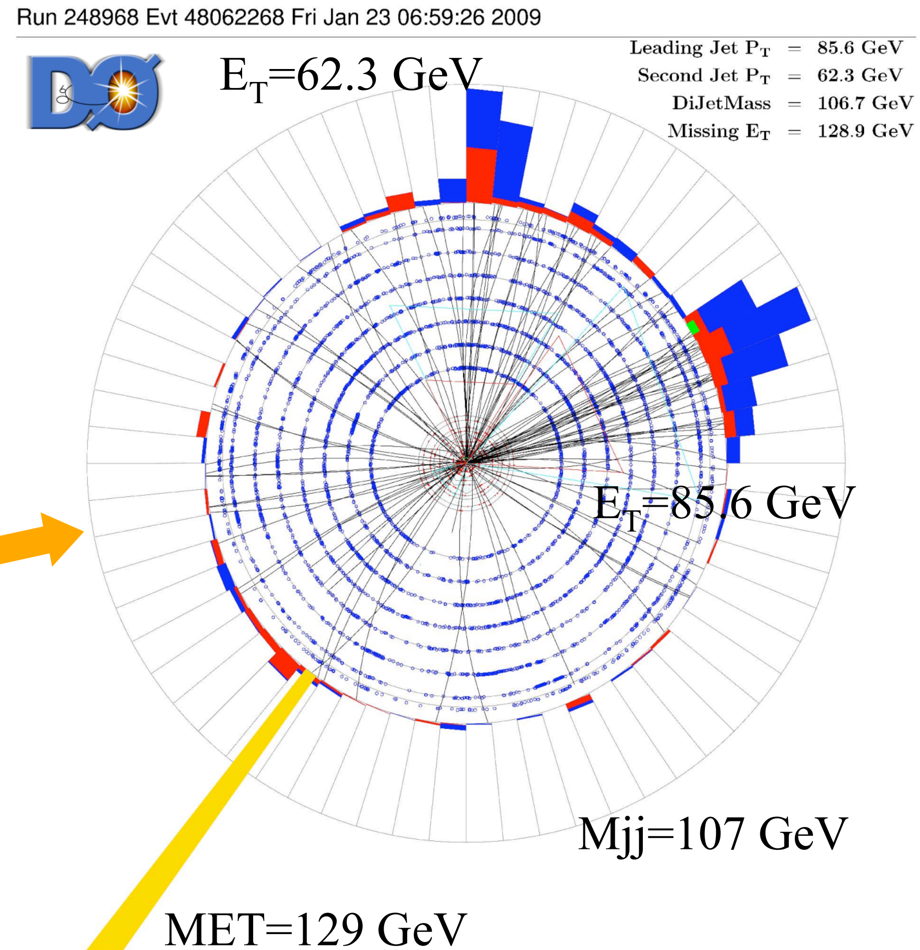
- Background:
  - Multi-jet } Fake MET due to instrumental effect
  - Top, W/Z+HF jets, Dibosons } Real MET



Missing Transverse Energy + Jets Final State

- Employ Multivariate Discriminant to separate signal from background



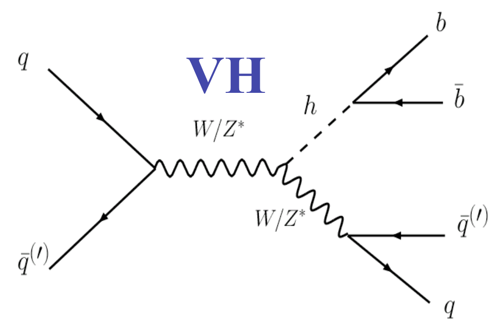


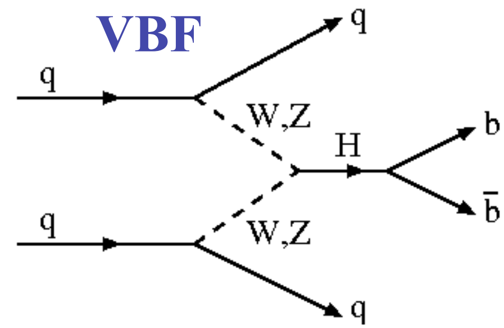
Both jets are b-tagged

m=115 GeV/c²	∫L (fb⁻¹)	Expected Limit	Observed Limit
CDF	3.6	4.2	6.1
DØ	5.2	4.6	3.7

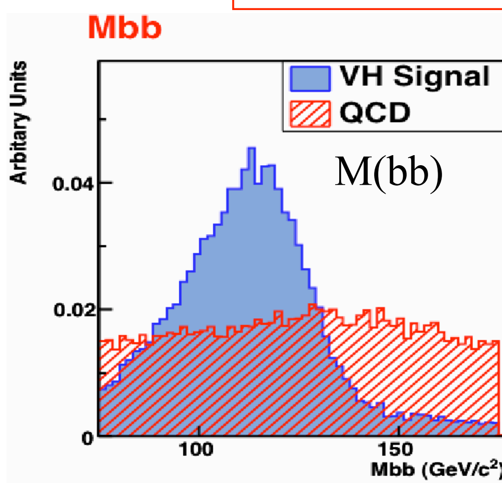
qqbb Final State

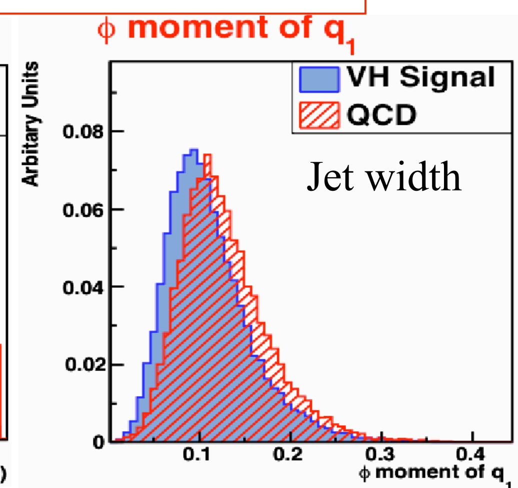
- Signal from associated (VH) and vector boson fusion (VBF) productions
- **Advantage** : Large signal yield, fully reconstructible final state
- **Disadvantage** : Huge multi-jet background
- Event selection: ≥4 jets, 2 b-tagged jets
- Train NN to separate multi-jet from Higgs

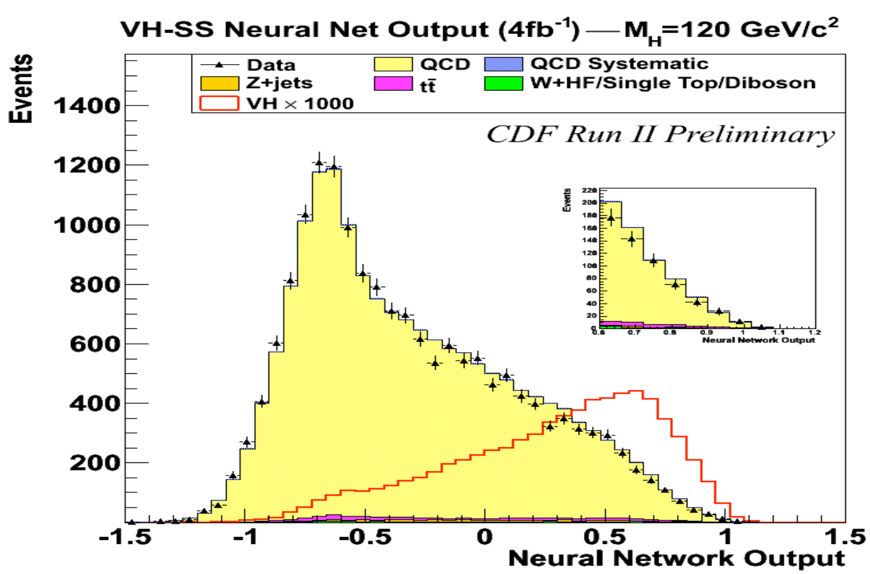




Variables used in NN training







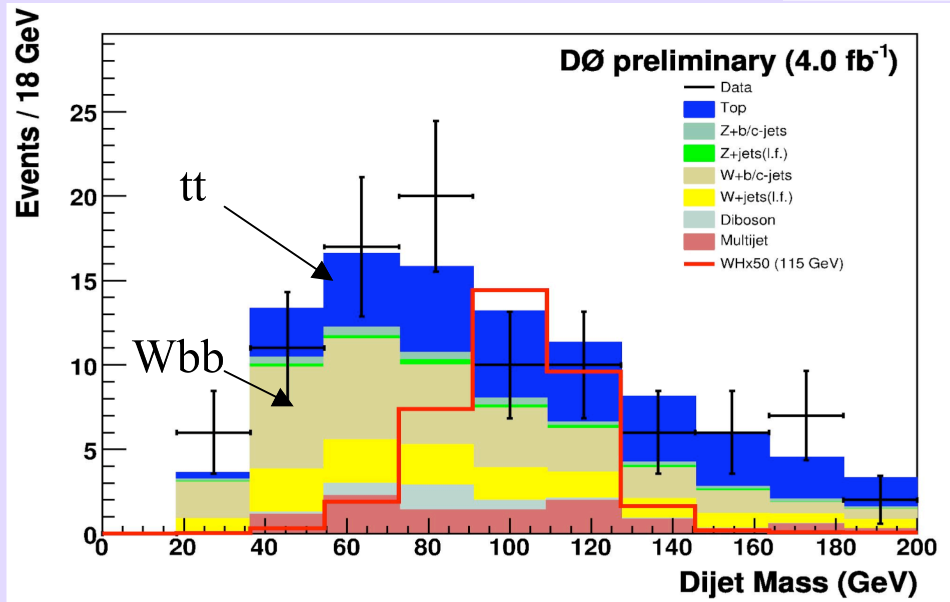
m=120 GeV/c²	∫L (fb⁻¹)	Expected Limit	Observed Limit
CDF	4.0	19.9	10.4

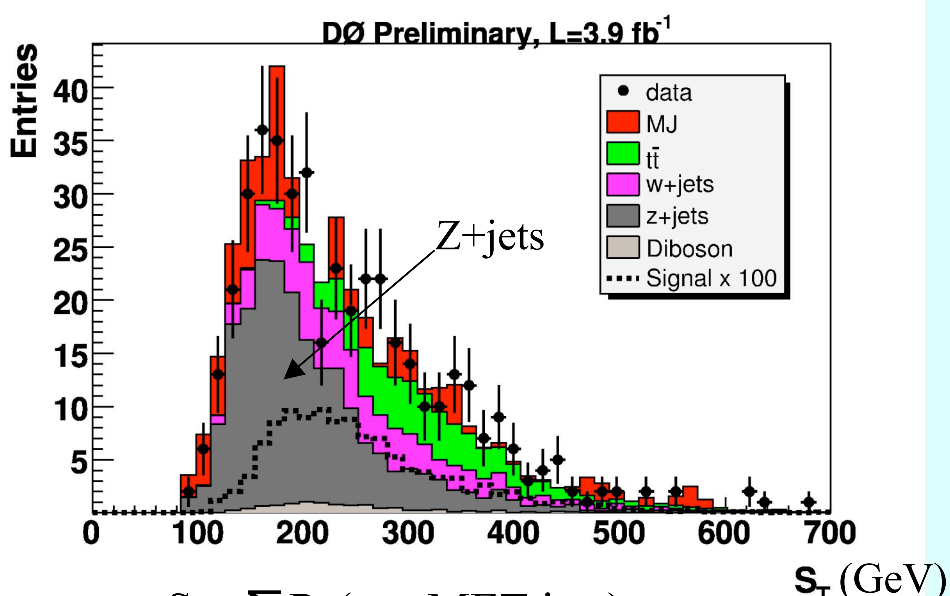
τ+MET+bb, ττqq Final State

τ+MET+bb get contributions from :

- WH→τνbb
- ZH→ττbb (one τ is not identified)

- Select events:
  - 1 hadronic τ, MET, ≥2 jets, ≥1 b-tag
- Limits(m=115 GeV, 4 fb^{-1}):
  - Observe (expect) 14.1 (22.4)





$S_T = \Sigma P_T(\mu, \tau, MET, jets)$

ττqq get contributions from :

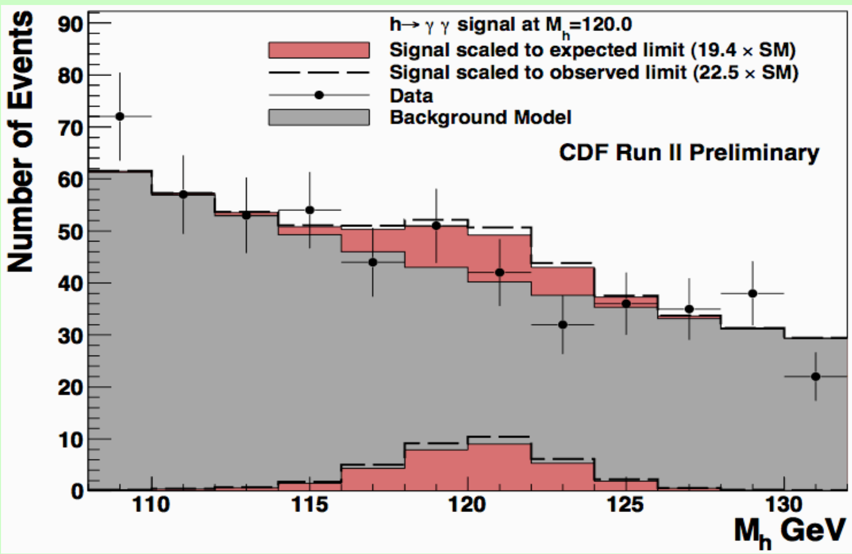
- ZH→ττqq, ZH→qqττ, WH→qqττ, VBF(H→ττ), gg→H+jets→ττ+jets
- Select events: 2 τ (one hadronic τ, one decays to $\mu\nu_\mu\nu_\tau$) , ≥2 jets
- Limits(m=115 GeV, 4.9 fb^{-1}):
  - Observe (expect) 27.0 (15.9)

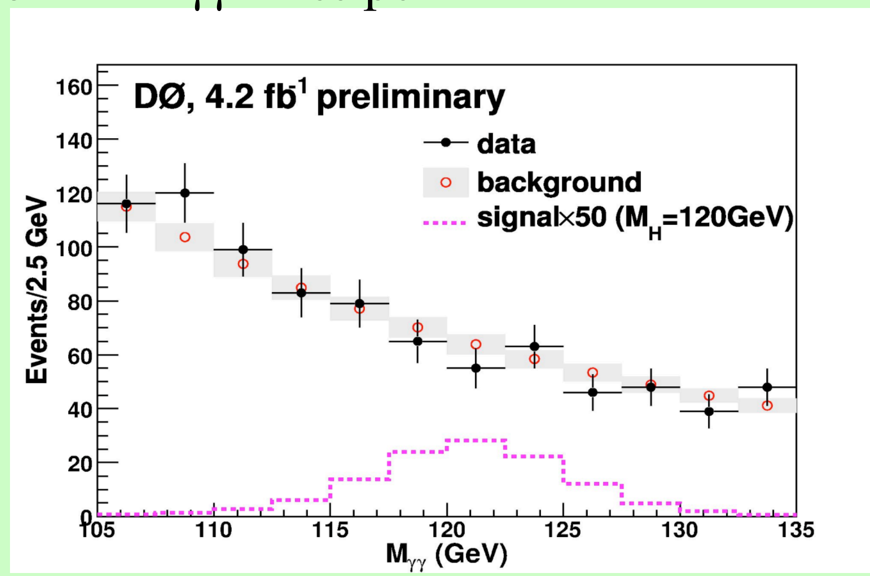
γγ+X Final State

- Signal contributions from :
  - gg→H→γγ
  - WH/ZH, H→γγ
  - qq→qqH (VBF), H→γγ

- Select events with ≥2 photon candidates
- Background:
  - Direct QCD di-photon
  - γ+jet, di-jet : jet fakes as γ
  - Z/γ*→ee, e mis-identified as γ

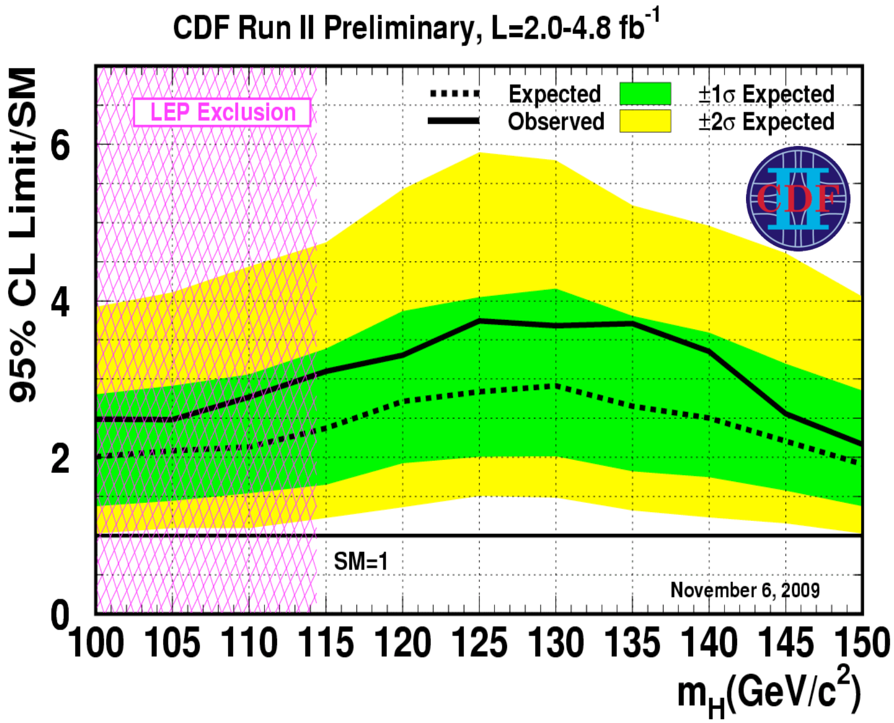
- Scan in a di-photon mass window to search for a H→γγ mass peak

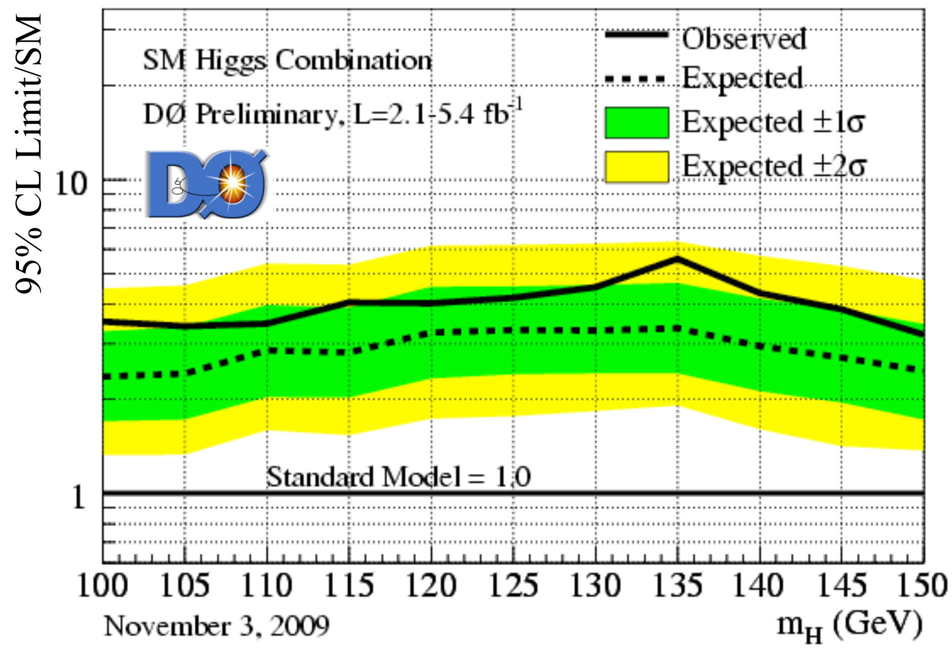




m=120 GeV/c^2	∫L (fb^{-1})	Expected Limit	Observed Limit
CDF	5.4	19.4	22.5
DØ	4.2	17.5	13.1

Combined Search Results From Each Experiment

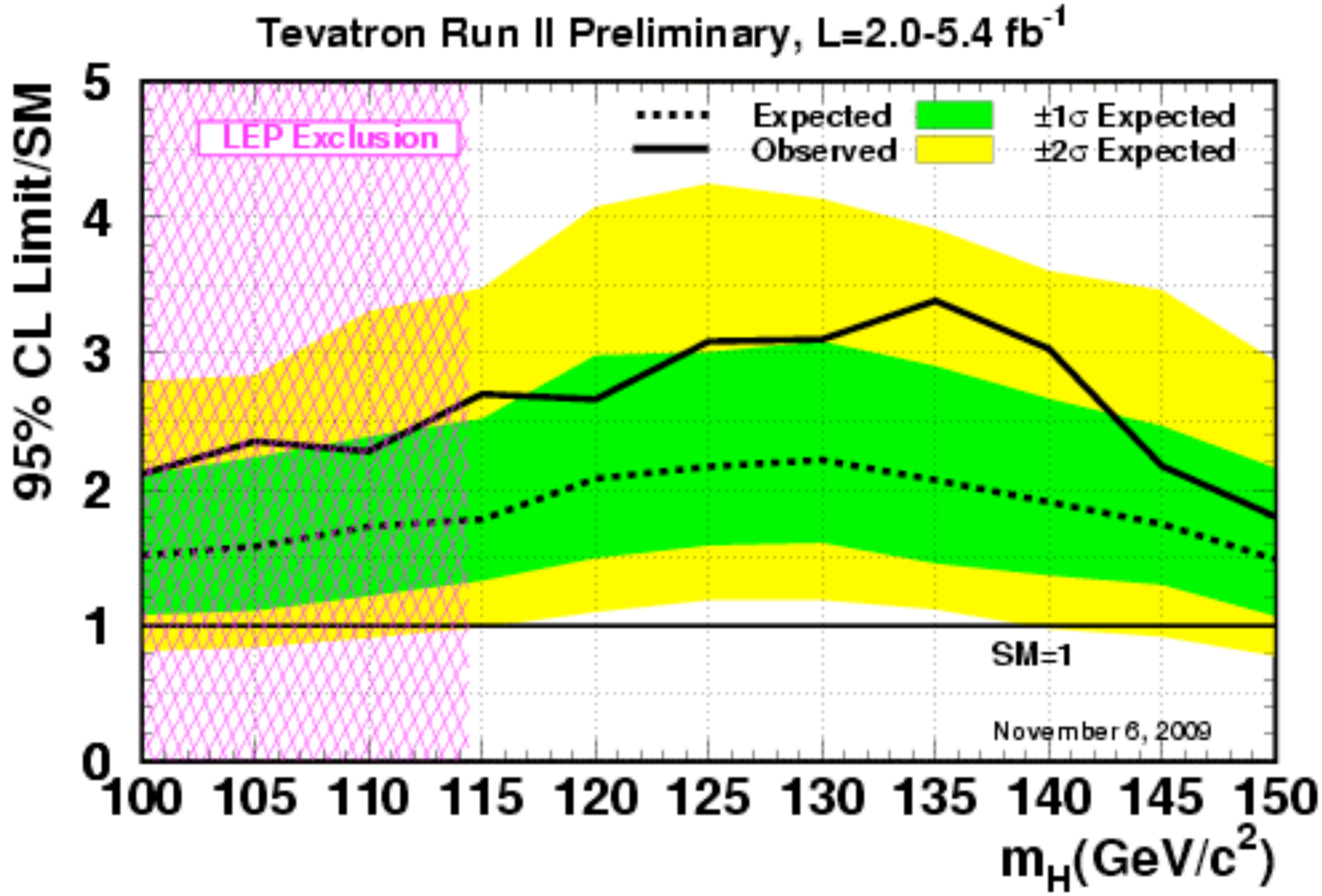




Mass=115 GeV/c^2	Expected Limit	Observed Limit
CDF	2.38	3.12
DØ	2.80	4.05

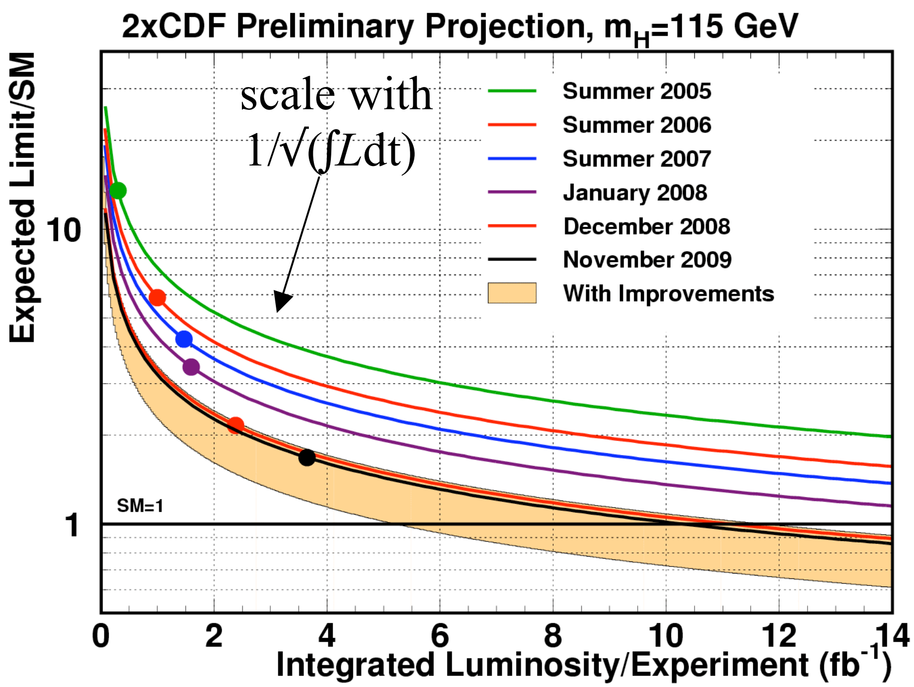
- Limits at low mass also receive contributions from high mass $H \rightarrow WW$ searches (Maiko Takahashi's talk)

Tevatron Combined Search Results

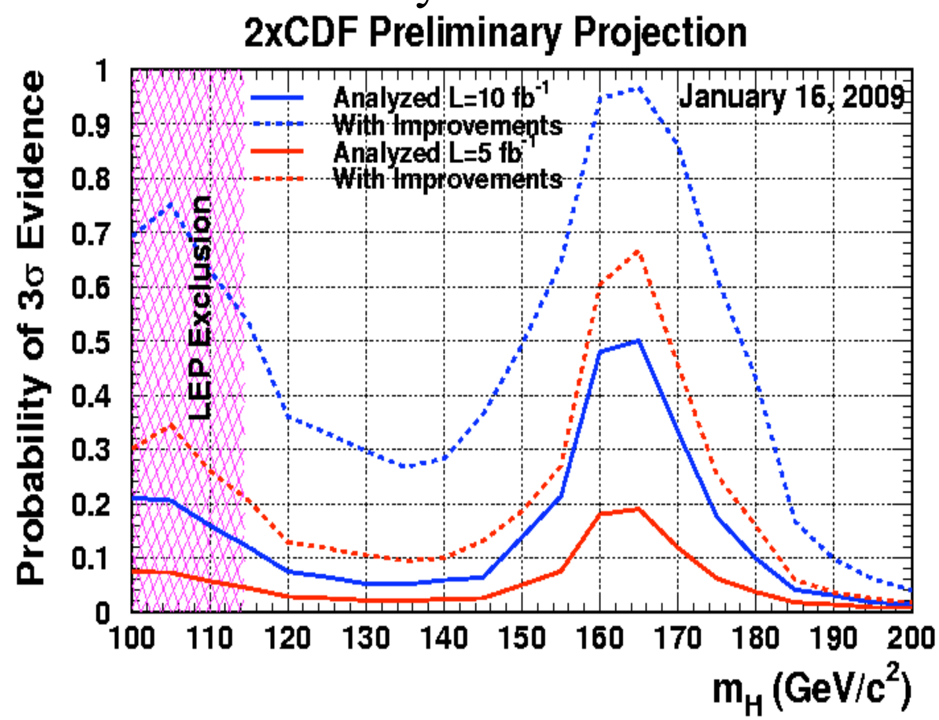


Mass=115 GeV/c^2	Expected Limit	Observed Limit
CDF+DØ	1.78	2.70

Higgs Boson Search Projection



Probability of 3σ Evidence



- Improvements are faster than $1/\sqrt{\int L dt}$ (gain from increasing data size)
  - Due to better analysis techniques
- Band indicates possible improvements.
- Tevatron may exclude Higgs (@ 115 GeV) with $\int L dt \sim$ 6-10 fb^{-1}

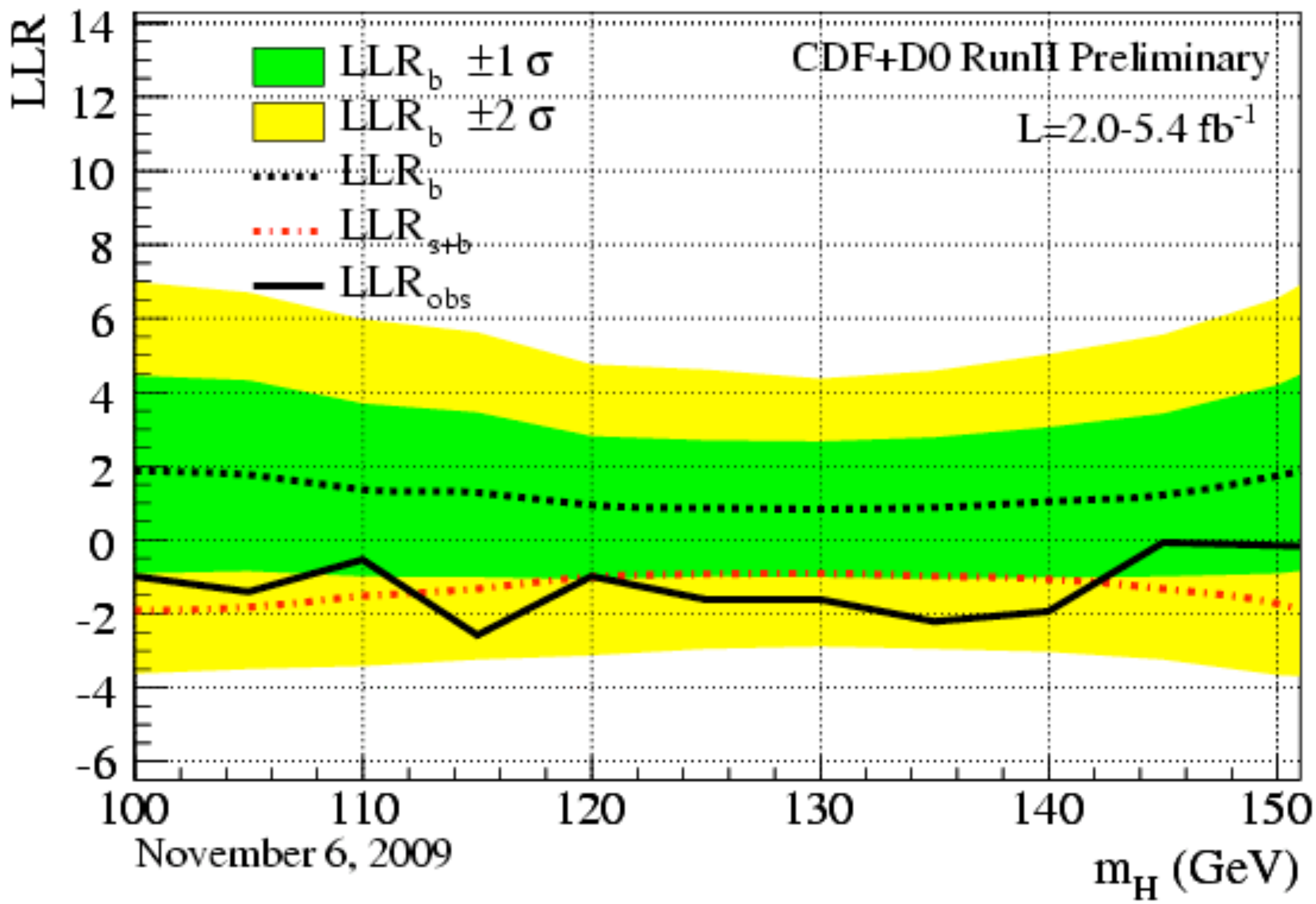
- With 10 fb^{-1} for each experiment and including all improvement techniques :
  - ~35% chance to observe 3σ evidence in low mass region

Summary

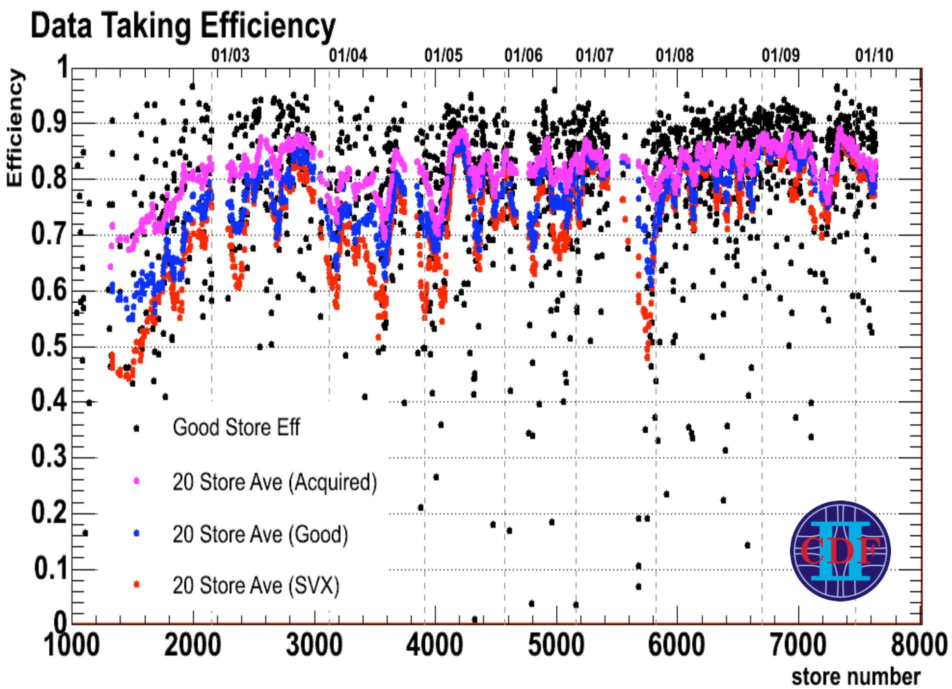
- CDF and DØ are pursuing extensive direct searches for the SM Higgs boson
- Exploring all possible search channels for low mass Higgs boson
- Combined Tevatron sensitivity is below 2*SM (for M(H)=115 GeV/c^2)
- Tevatron is expected to deliver ~10-12 fb^{-1} by end of 2011
- May have a chance to find evidence of Higgs in the low mass region if it exists there

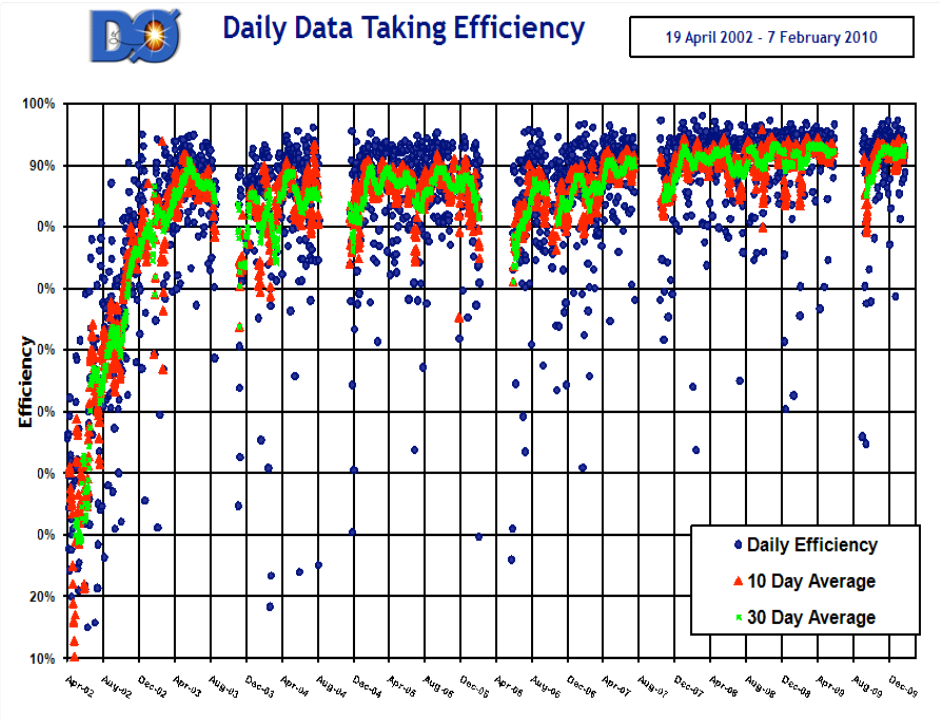
Back-UP

Tevatron Combined Search Results

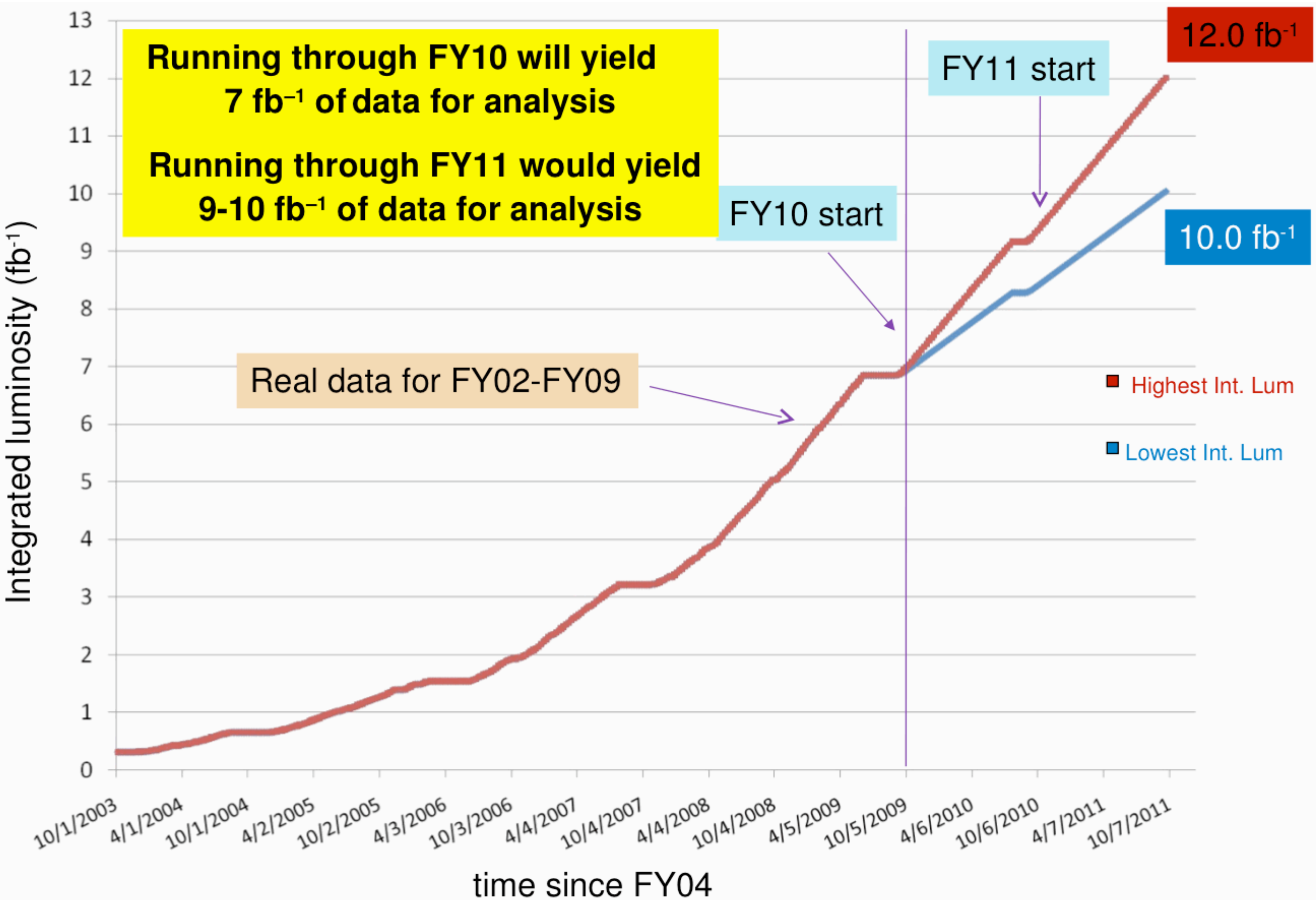


Experiments' Performance



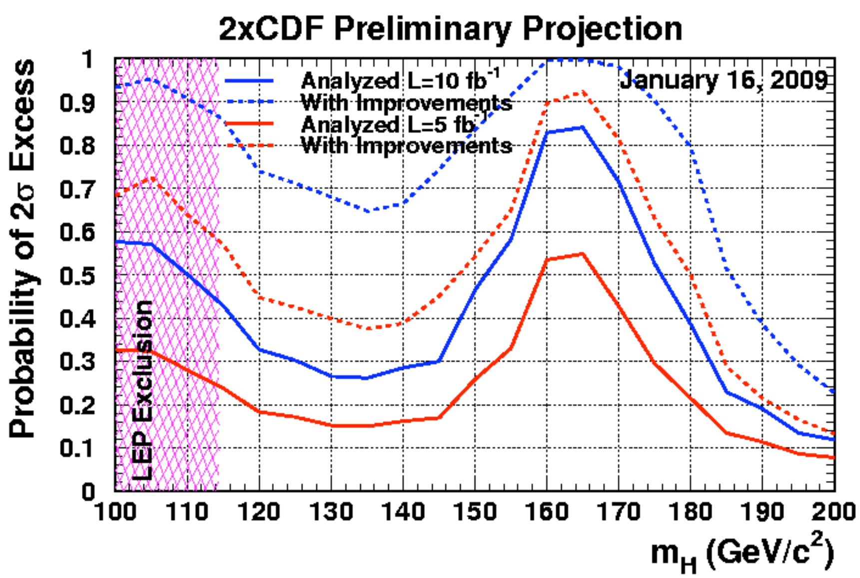


Tevatron Luminosity Projection

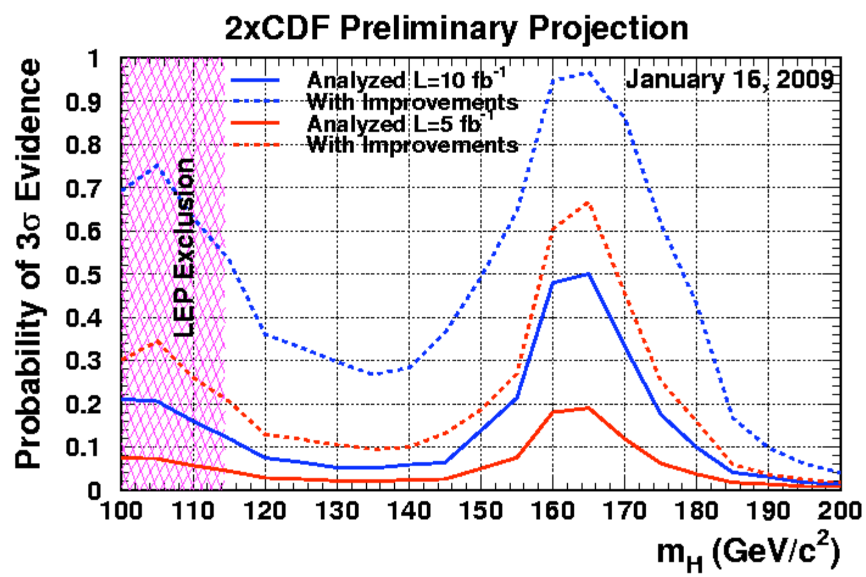


Higgs Boson Search Projection

Probability of 2σ Excess



Probability of 3σ Evidence



- With 10 fb^{-1} for each experiment and including all improvement techniques :
  - ~70% chance to observe 2σ excess in low mass region
  - ~35% chance to observe 3σ evidence in low mass region

Matrix Element Discriminant

- Matrix Element (ME) probability : probability that an observed event is from a particular physics process

$P(x_{obs} | WH)$: probability of event from WH production

x_{obs} : measured quantities of the event

$$P(x_{obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma(y)}{dy} \varepsilon(y) G(x_{obs}, y) dy$$

y : true values of the observables

$d\sigma(y)/dy$: parton level differential cross section

$\varepsilon(y)$: detector acceptance & efficiency

$1/<\sigma>$: normalization constant

$G(x_{obs}, y)$: transfer function representing the detector resolution

- The true values of the observables are unknown, therefore we need to integrate over them

- Use probability values to compute likelihood :

$$L = \frac{P_S(x_{obs})}{P_S(x_{obs}) + \sum_i f_i \cdot P_i(x_{obs})}$$

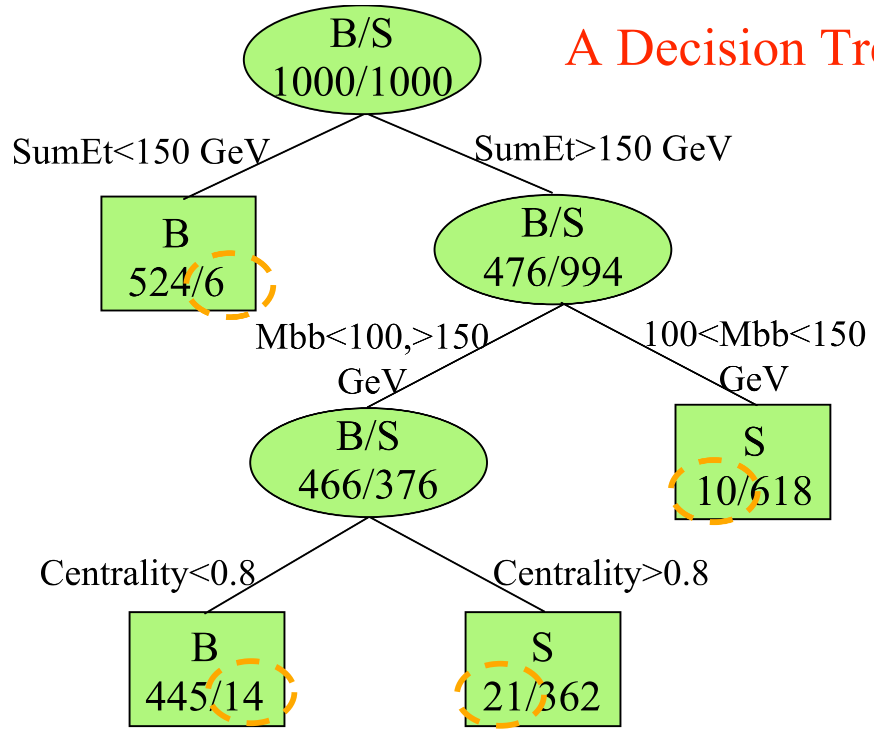
$P_S(x_{obs})$: probability of event to be signal

$P_i(x_{obs})$: probability of event to be background *i*th

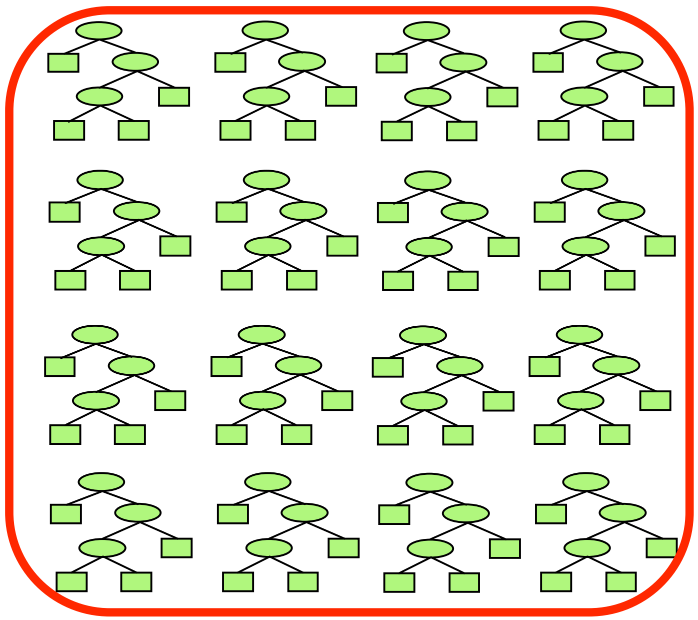
f_i : fraction from background *i*th

Boosted Decision Tree

- Training a decision tree:
  - Events of equal weight pass through a cascade of cuts
  - Eventually events land on signal (S) or background (B) leaf node
  - Events landed in wrong leaf node (e.g. signal event land in BG node) are given larger weights (boosted)
  - Tree is retrained, may build up 100-1000 tress
- Trained decision trees are used to classify an event:
  - A discriminant value is givent to an event based on the weighted sum of all the trees (weight is the boost-weight)



A Decision Tree



A forest of Decision Trees