Search for SM Higgs at DØ

Michael Kirby

Northwestern University

Virginia HEP Seminar, December 3, 2008

Search for SM Higgs at DØ

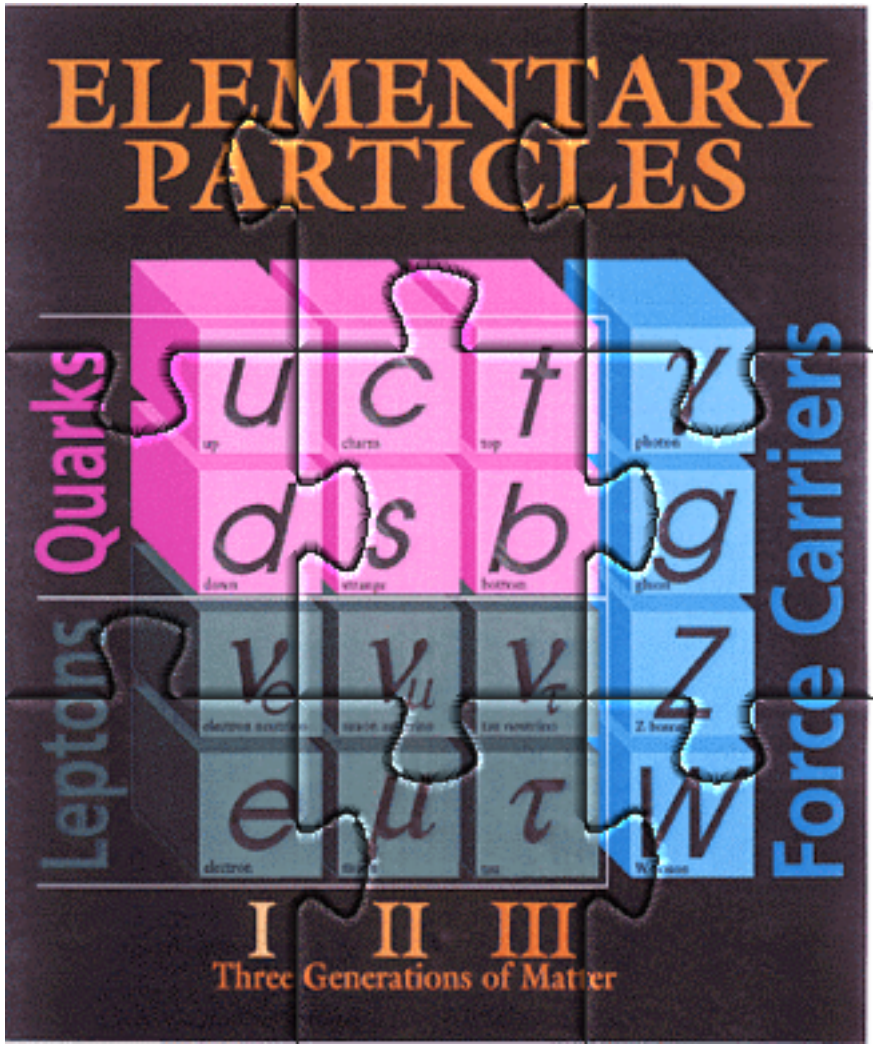
Are we getting smarter fast enough?

Michael Kirby

Northwestern University

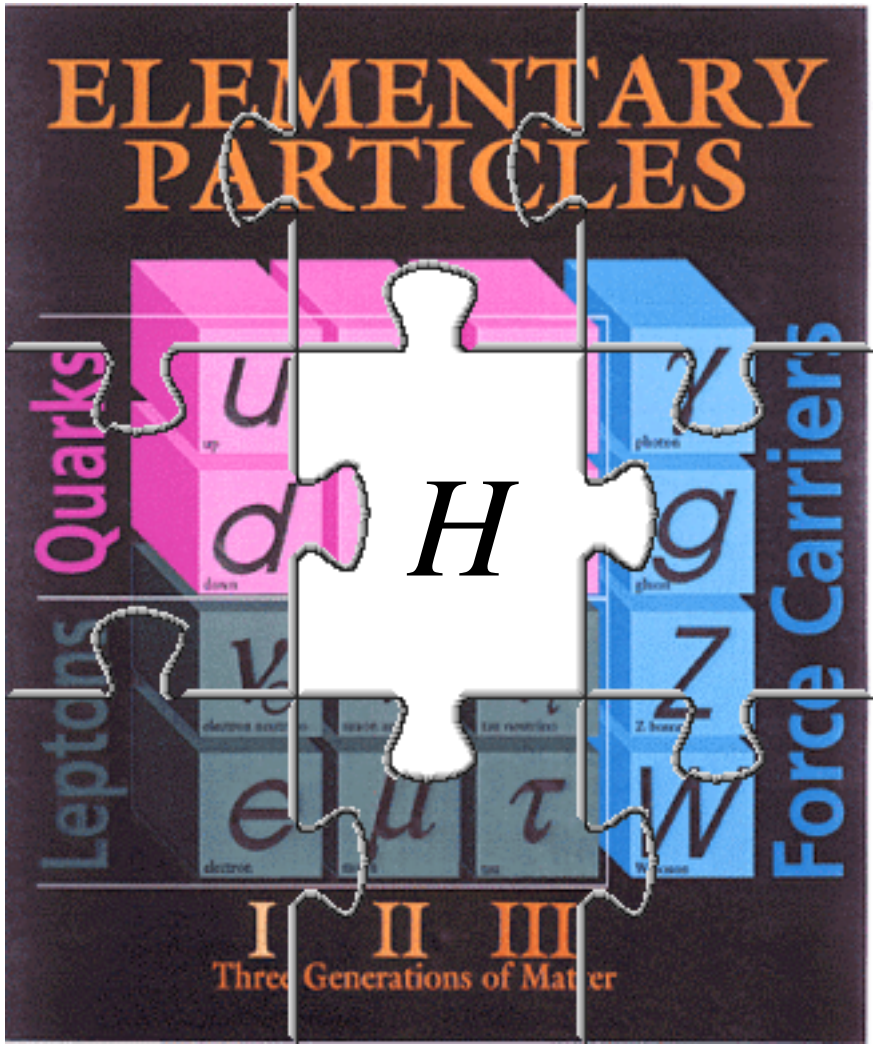
Virginia HEP Seminar, December 3, 2008

The Standard Model of Particle Physics



- Gauge field theory
  - 3 generations of fermions
  - 4 gauge bosons
  - Strong $SU(3)_c$
  - Electroweak $SU(2)_L x U(1)_Y$
- Extremely successful
  - Predicted W, Z, and top
  - Tested to per mille precision
- Incomplete Theory
  - Gravity?
  - Grand Unification?
  - Dark Energy, Dark Matter?

The Missing Piece



- Need a mechanism to generate particle mass
- Electroweak Symmetry Broken
  - W/Z massive
  - γ,g massless
- Measuring the EWK symmetry breaking critical to current and future collider experiments
- Simplest Model is the Higgs mechanism

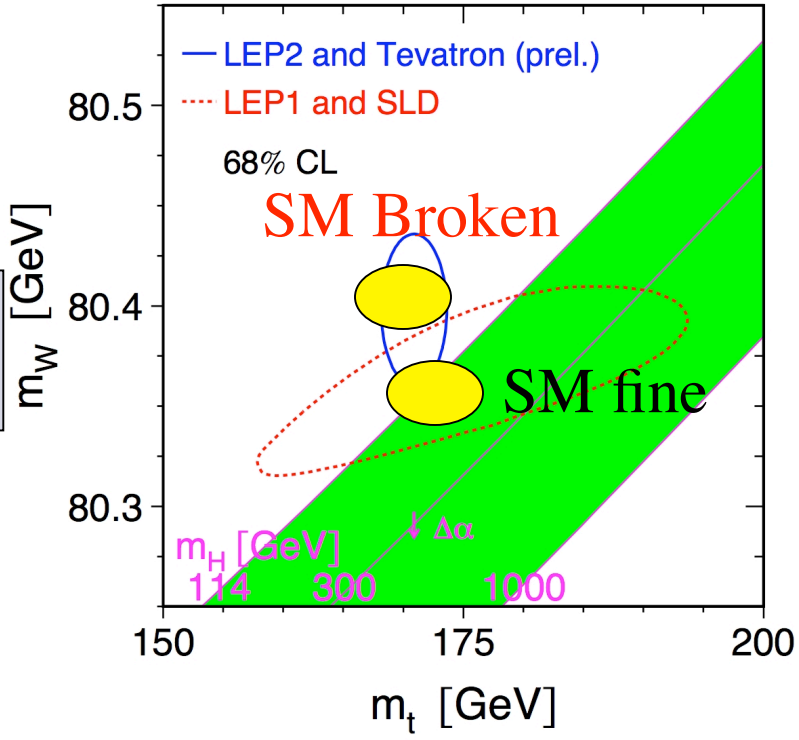
Precision SM Consistency Check

- Higgs and top contribute radiative corrections to M_W

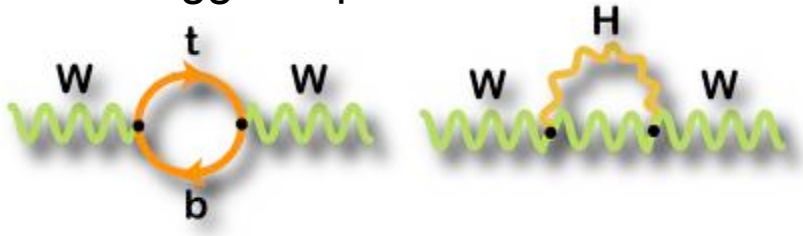
known to 0.015%

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\frac{1}{1-M_W^2/M_Z^2}\frac{1}{1-\Delta r}$$

known to 0.0009% M_Z known to 0.002%



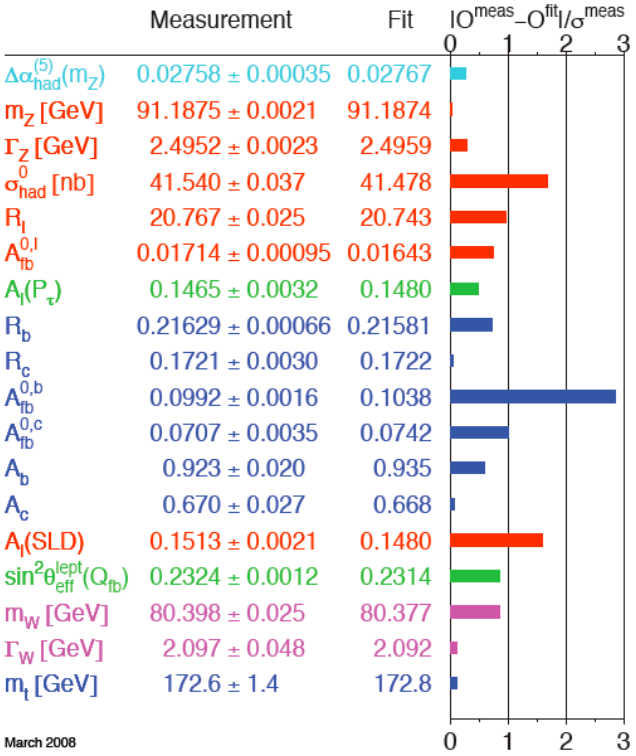
Δr: radiative corrections dominated by *tb* and Higgs loops



m_{top} =(170.9 ± 1.8) GeV (1.1%)
m_W=(80.389±0.025) GeV (0.031%)

Current Limits on Higgs Mass

Precision EWK measurements at Tevatron, LEP and SLD

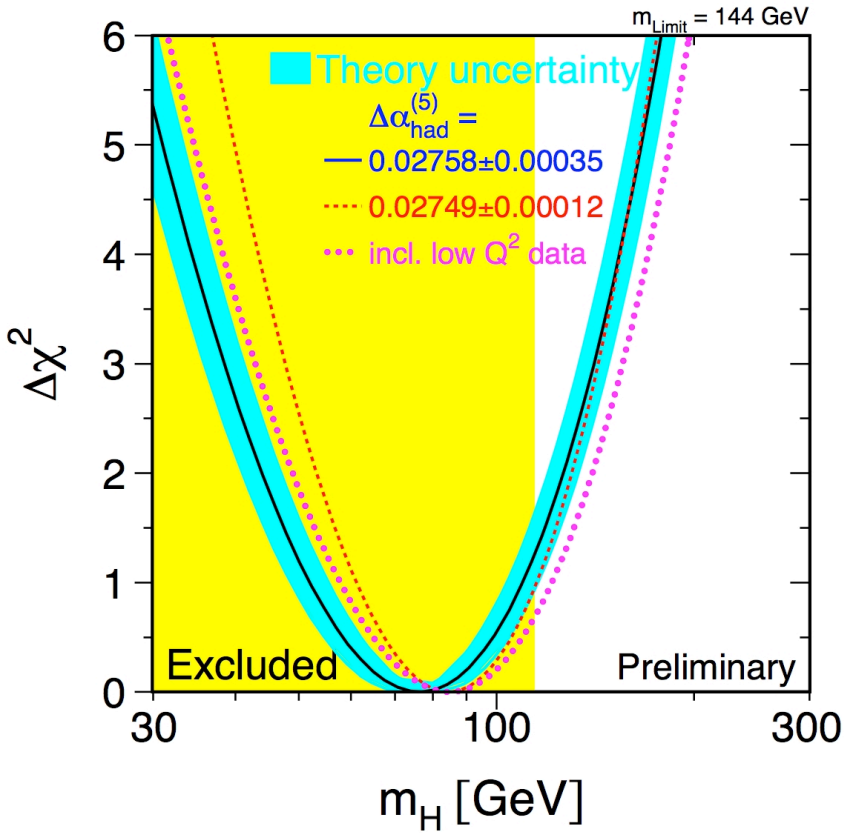


$m_H = 87^{+36}_{-27}$ GeV

$m_H < 160$GeV@ 95%CL

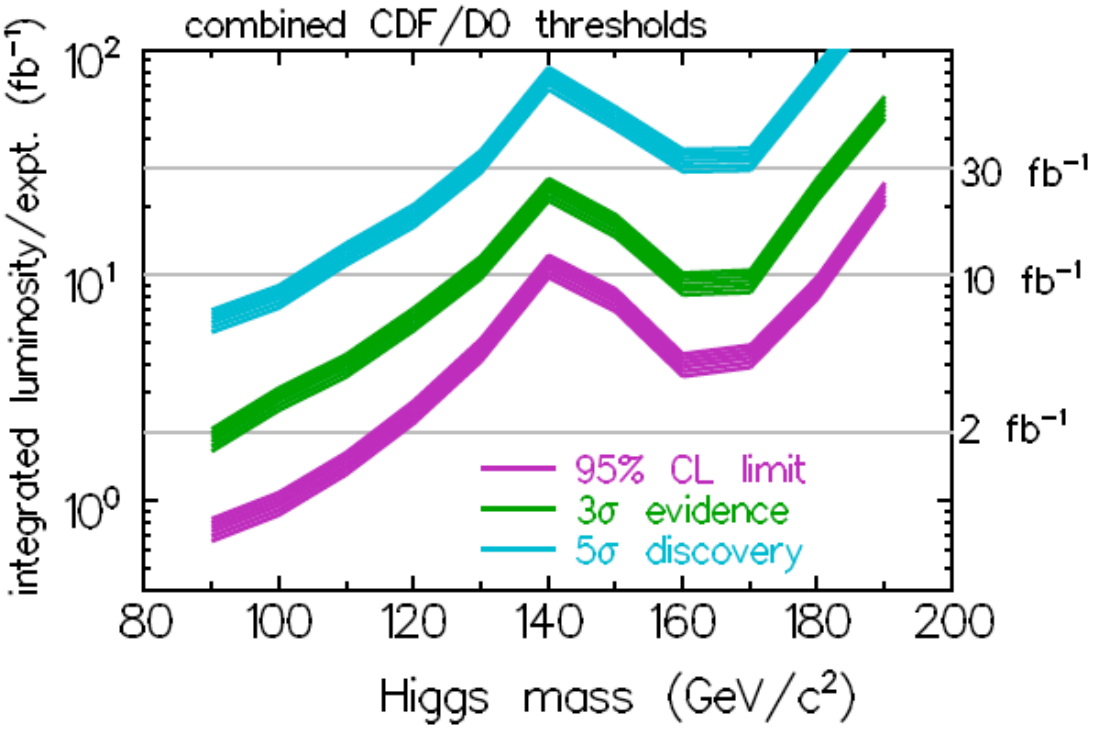
LEP Direct Search

$m_H > 114$GeV@ 95%CL



Are we getting smarter fast enough?

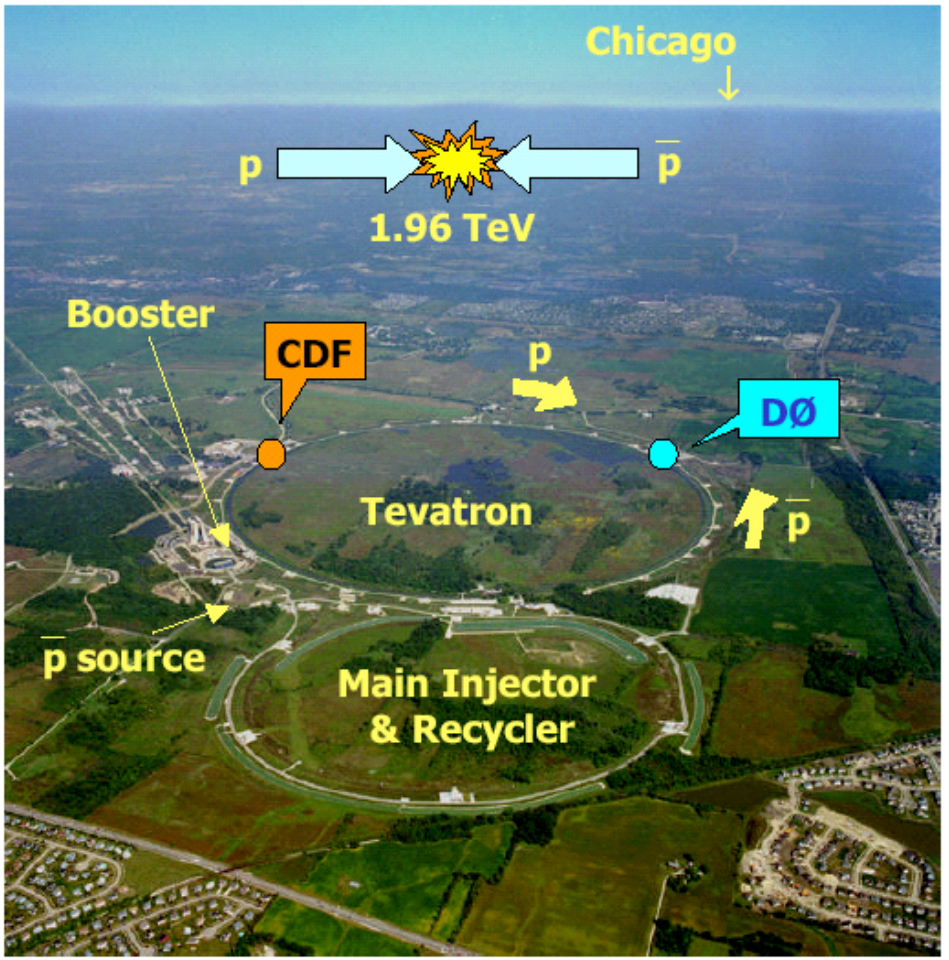
Given the above discussion, the basic conclusions arrived at below are not unreasonably aggressive. Breakthroughs in technique are always possible, and have indeed been the norm in the past. For example both the Higgs search in LEP1 and the top quark search in Run 1 at the Tevatron exceeded the expectations of studies prior to machine turn-on. The studies presented here should be taken as cautiously optimistic: Using full mass spectrum fits, applying neural network techniques, improving the trigger efficiencies, adding other search mode, and improving the mass resolution and tagging efficiency beyond that projected here may all serve to dramatically improve the discovery potential for the Higgs at the Tevatron.



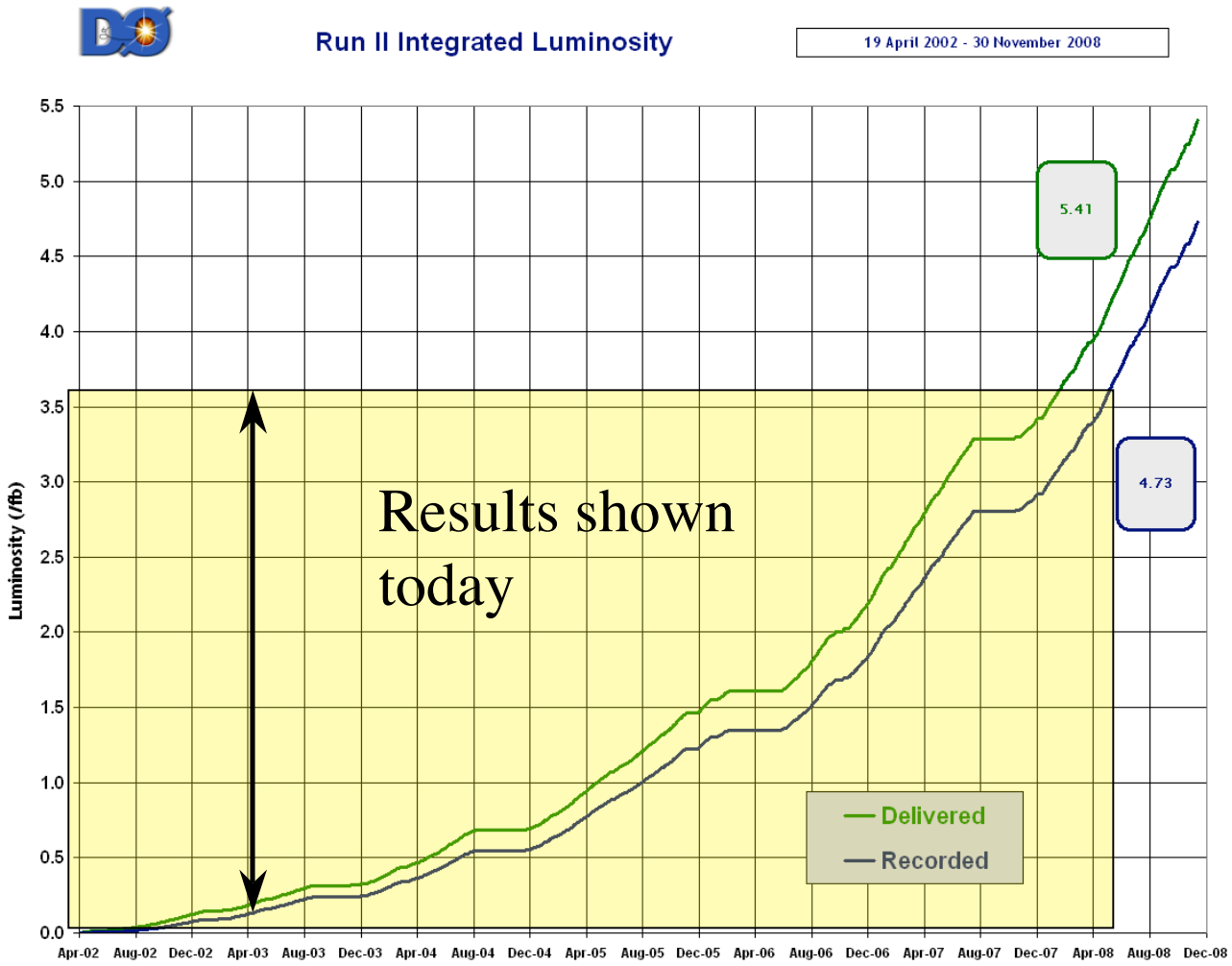
hep-ph/0010338v2

The Tevatron at Fermilab

- Tevatron proton-antiproton collider at Fermilab
  E_{Beam} = 980 GeV
  $\sqrt{s} = 1.96\text{TeV}$
- Current average initial:
  >300 x 10^{31} cm^{-2} s^{-1}
- Record: ~ 345 x 10^{30} cm^{-2} s^{-1}
- ~ 30 pb^{-1} per week
- Recorded in total $\int \mathcal{L}$ ~4 fb^{-1} per experiment
- Long term goal is 8 fb^{-1}

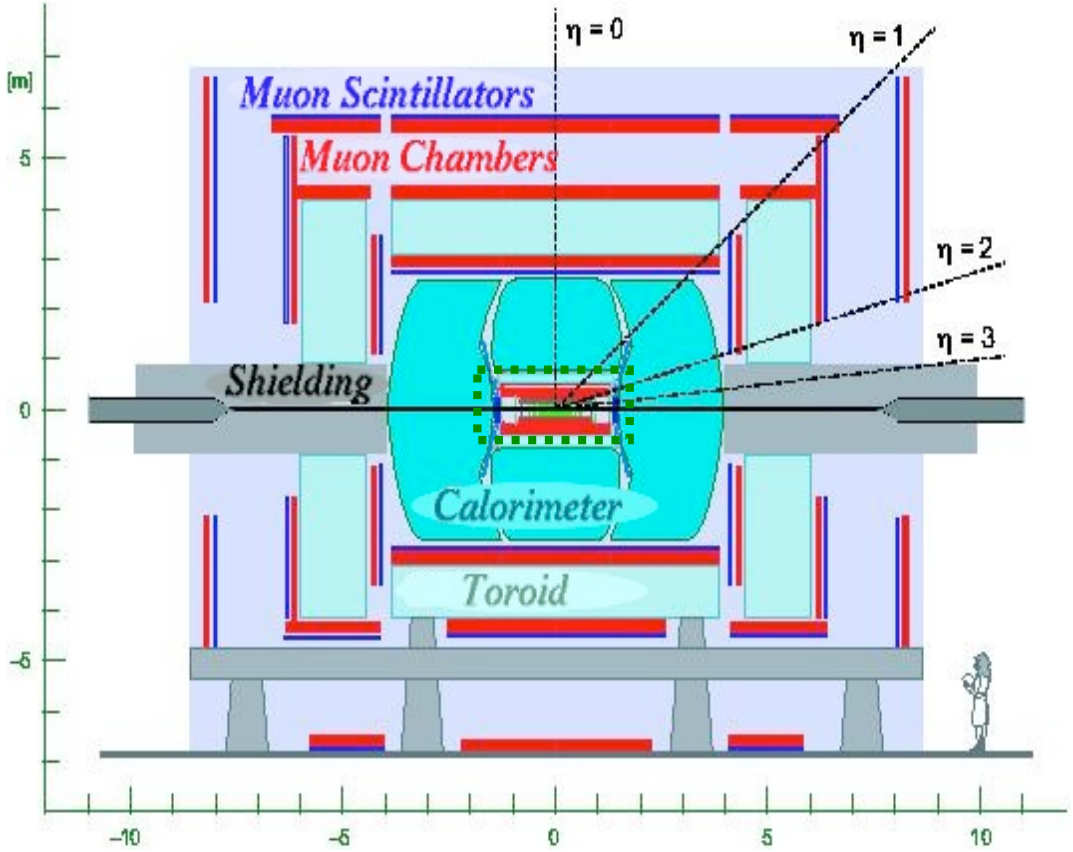


Integrated Luminosity at DØ



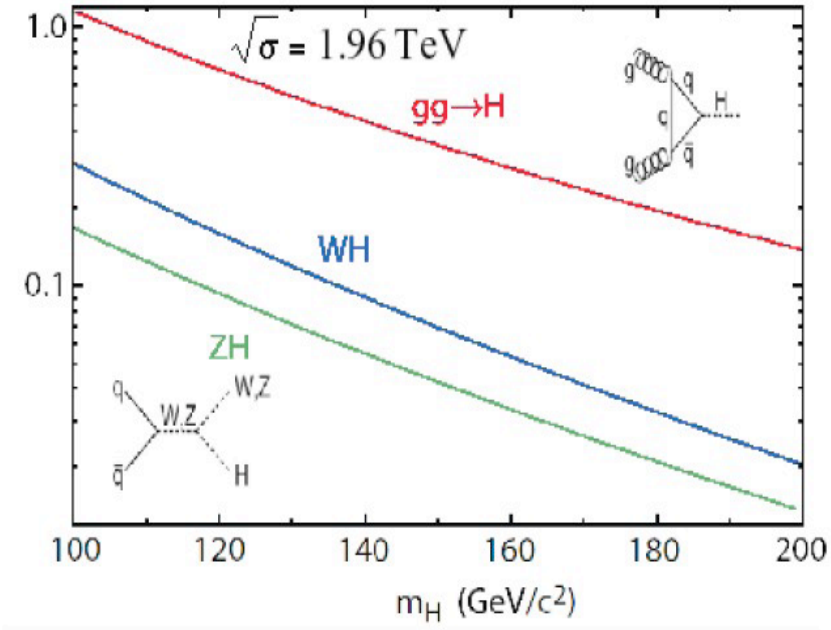
DØ Detector

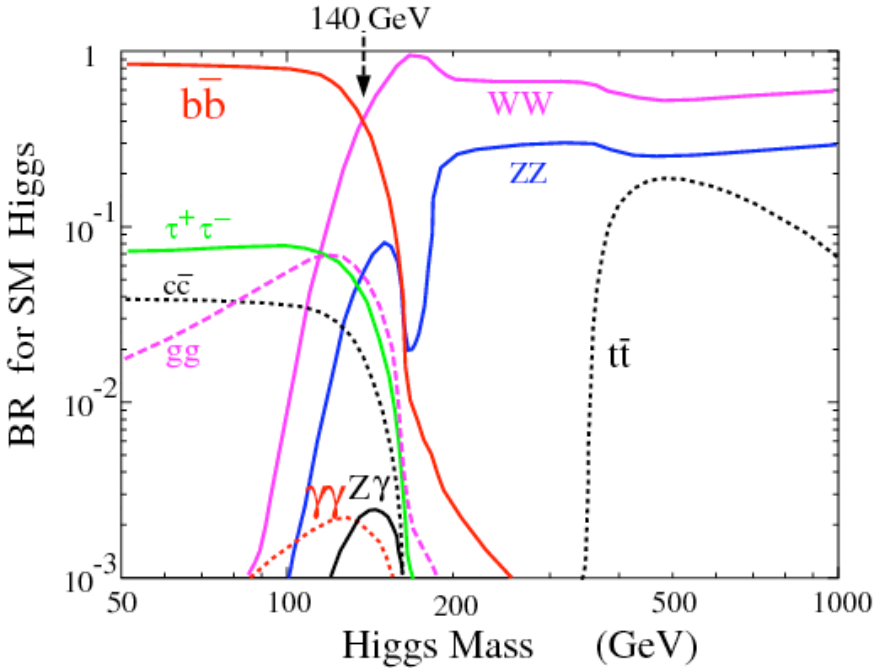
- **Spectrometer : Fiber and Silicon Trackers in 2 T Solenoid**
- **Energy Flow : Fine segmentation liquid Ar Calorimeter and Preshower**
- **Muons : 3 layer system & absorber in 1.8 T Toroidal field**
- **Hermetic : Excellent coverage of Tracking, Calorimeter and Muon Systems**



detector coverage |η|
muons ~ 2
tracking ~ 2.5
EM/Jet ~ 4

Higgs Production at the Tevatron





Gluon fusion through quark loop dominates, NNLO corrections considerable

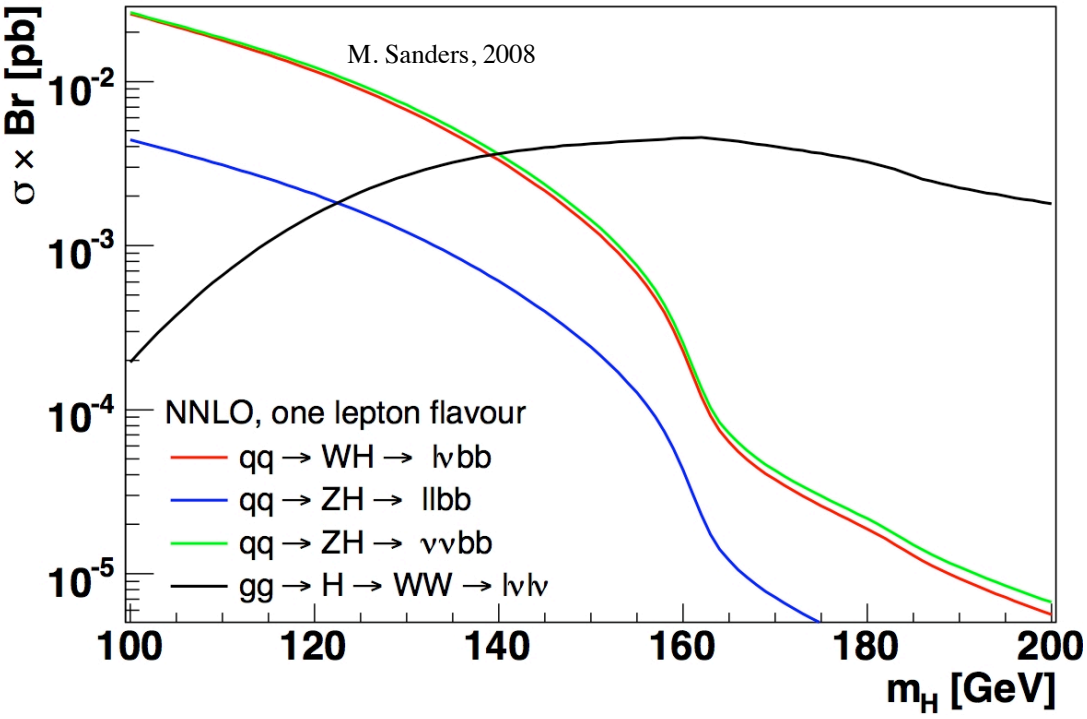
Associated production with a massive boson

Higgs couples to mass, and so decays to heavier particles

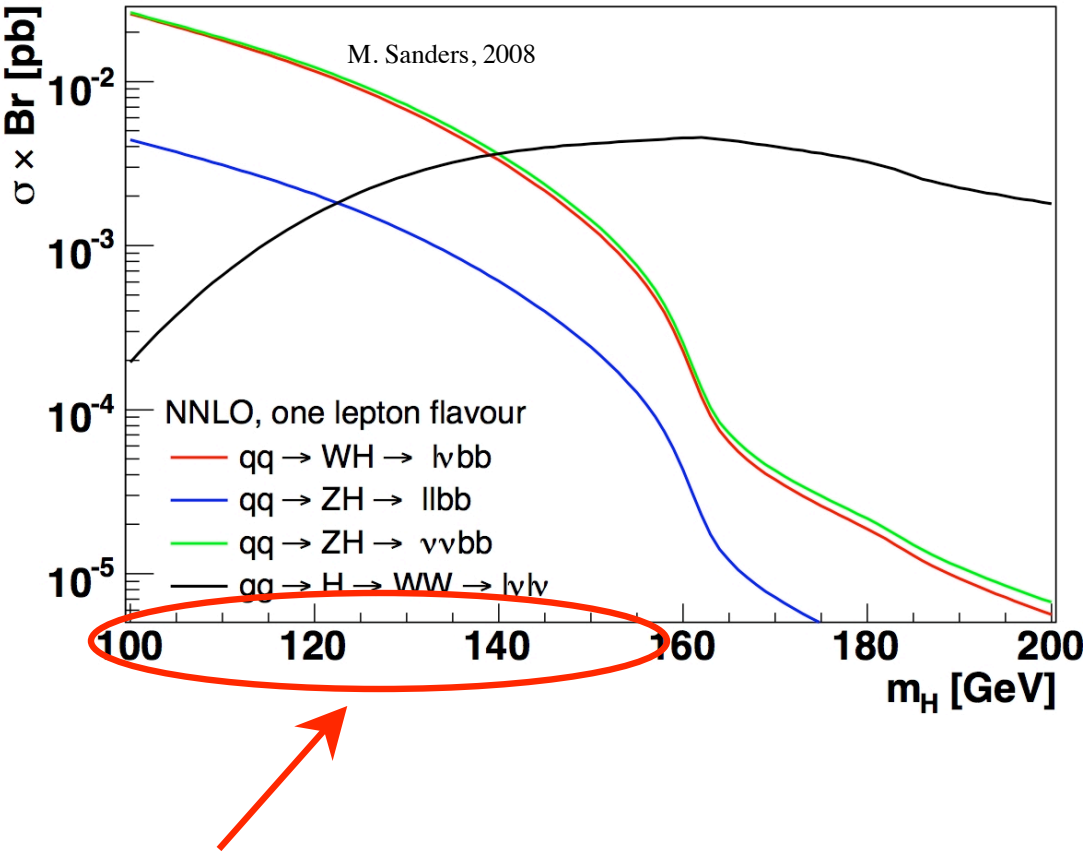
For M_H<140, H→bb dominates

Above 140, H->WW dominates

Higgs Final State Signatures

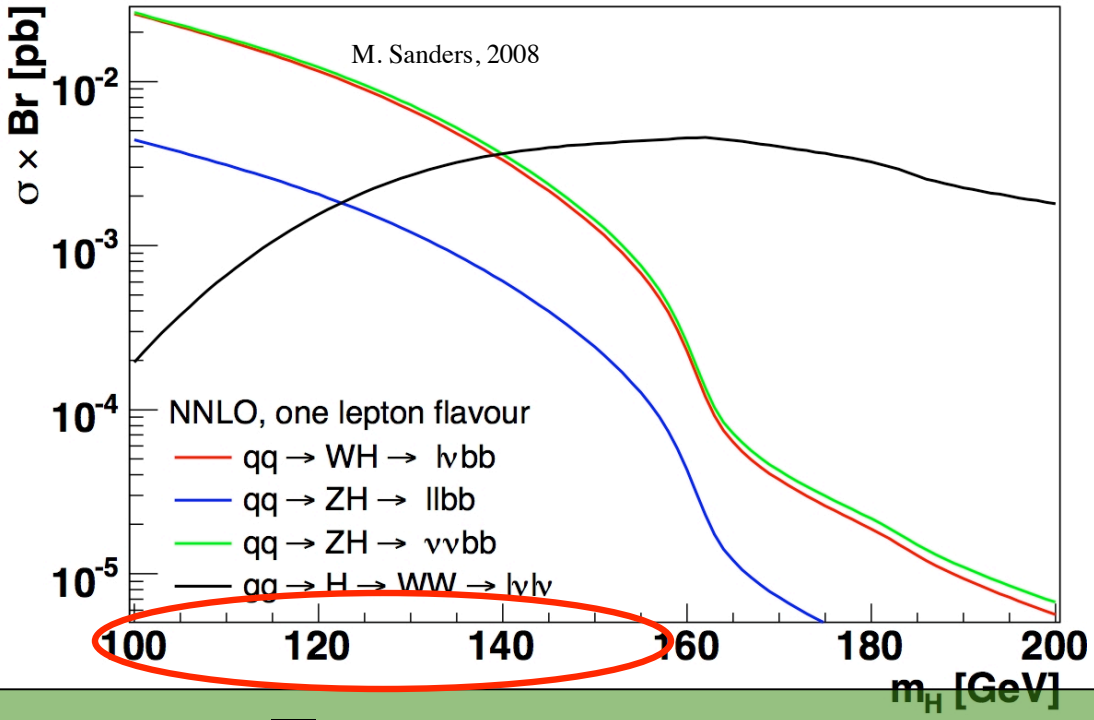


Higgs Final State Signatures



Low Mass Higgs →(100,140)

Higgs Final State Signatures



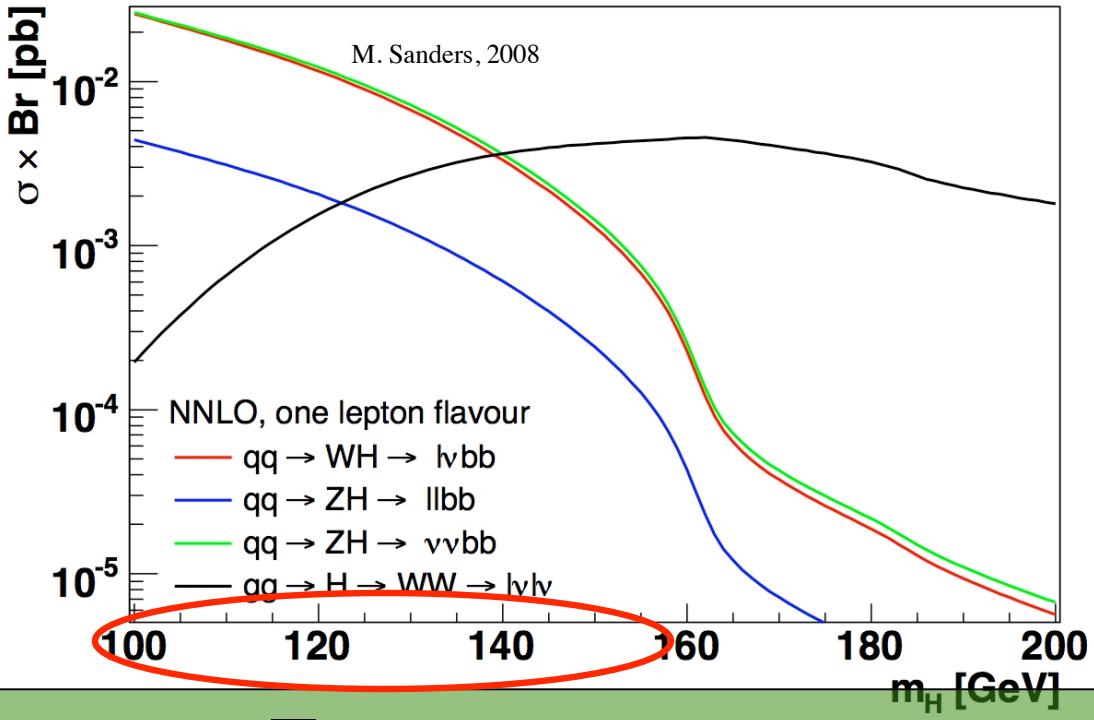
$WH \rightarrow l\nu b\bar{b}$ ⇒ Lepton + Met + b-jets

$ZH \rightarrow ll b\bar{b}$

$ZH \rightarrow \nu\nu b\bar{b}$

$WH \rightarrow (l)\nu b\bar{b}$

Higgs Final State Signatures



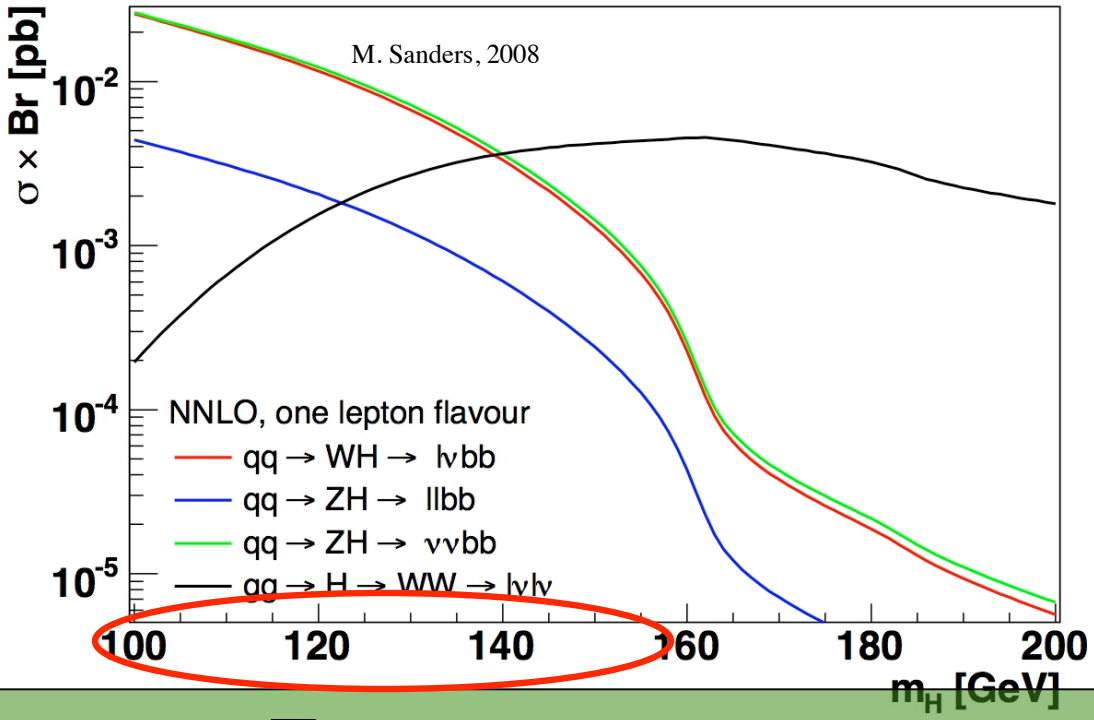
$WH \rightarrow l\nu b\bar{b}$ ➡ Lepton + Met + b-jets

$ZH \rightarrow ll b\bar{b}$ ➡ DiLepton + b-jets

$ZH \rightarrow \nu\nu b\bar{b}$

$WH \rightarrow (l)\nu b\bar{b}$

Higgs Final State Signatures



$WH \rightarrow l\nu b\bar{b}$ ⇒ Lepton + Met + b-jets

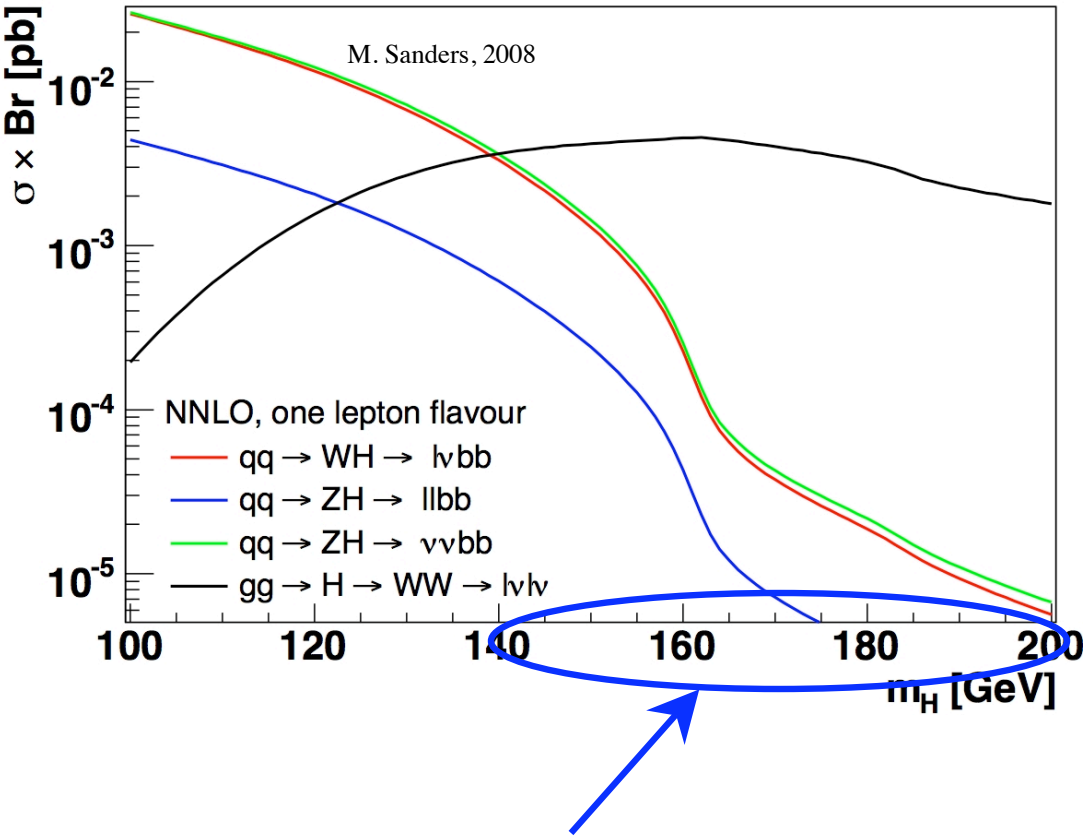
$ZH \rightarrow ll b\bar{b}$ ⇒ DiLepton + b-jets

$ZH \rightarrow \nu\nu b\bar{b}$

$WH \rightarrow (l)\nu b\bar{b}$

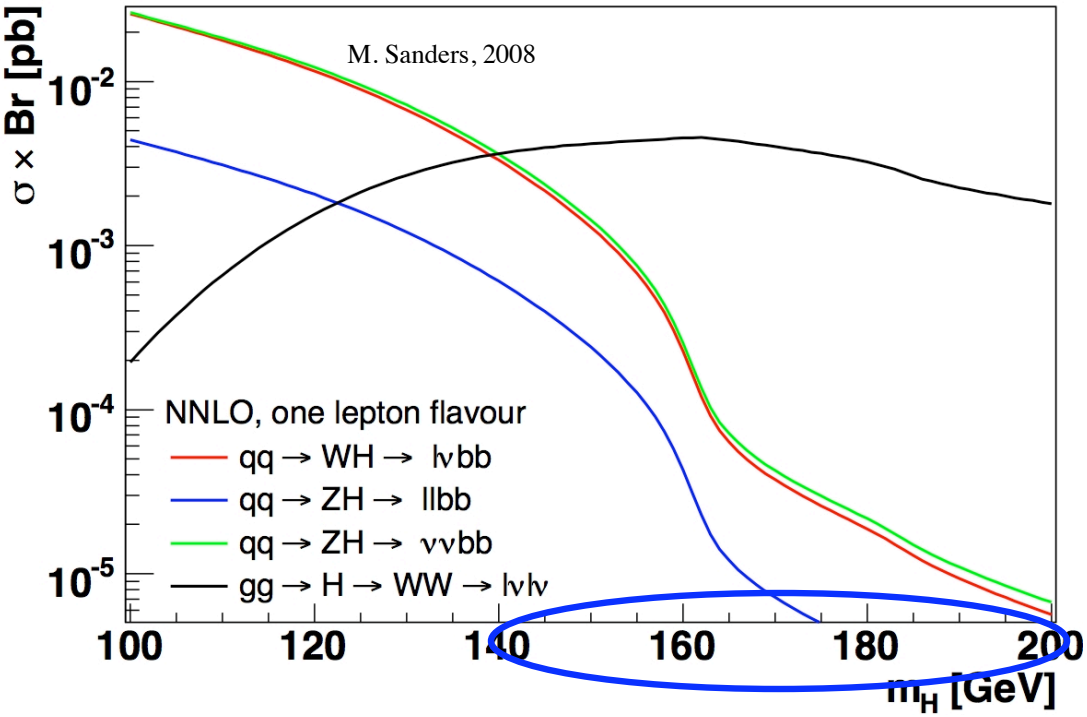
⇒ Met + b-jets

Higgs Final State Signatures



High Mass Higgs →(140,190)

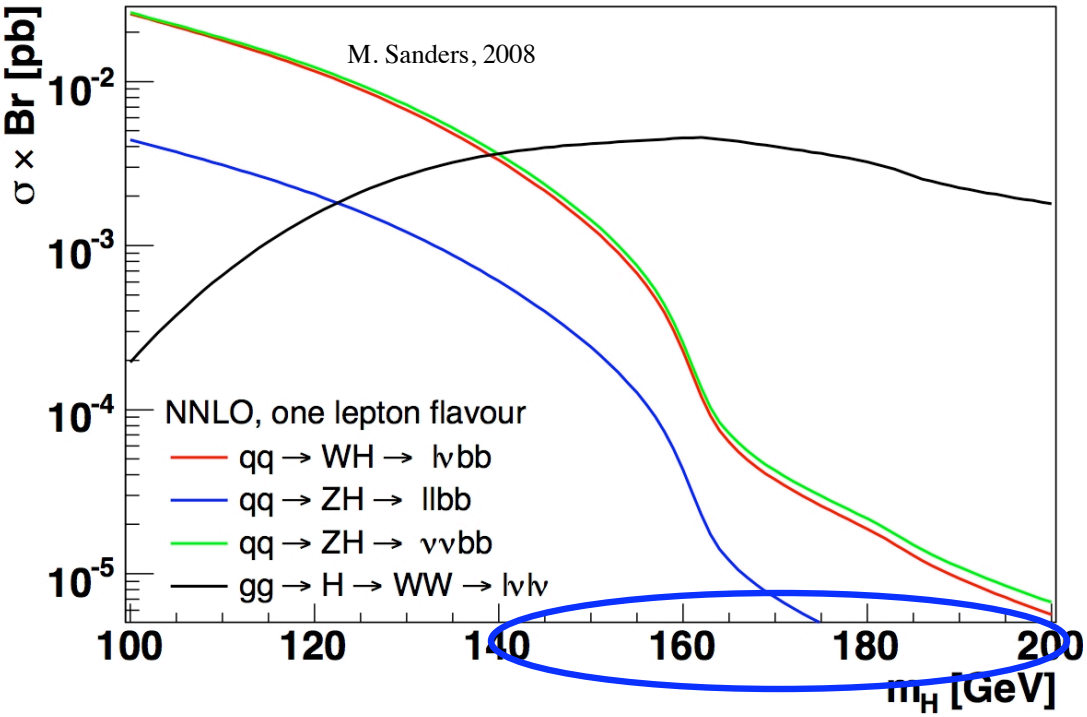
Higgs Final State Signatures



WH →WWW ➡Like Sign Leptons + Met

H → WW

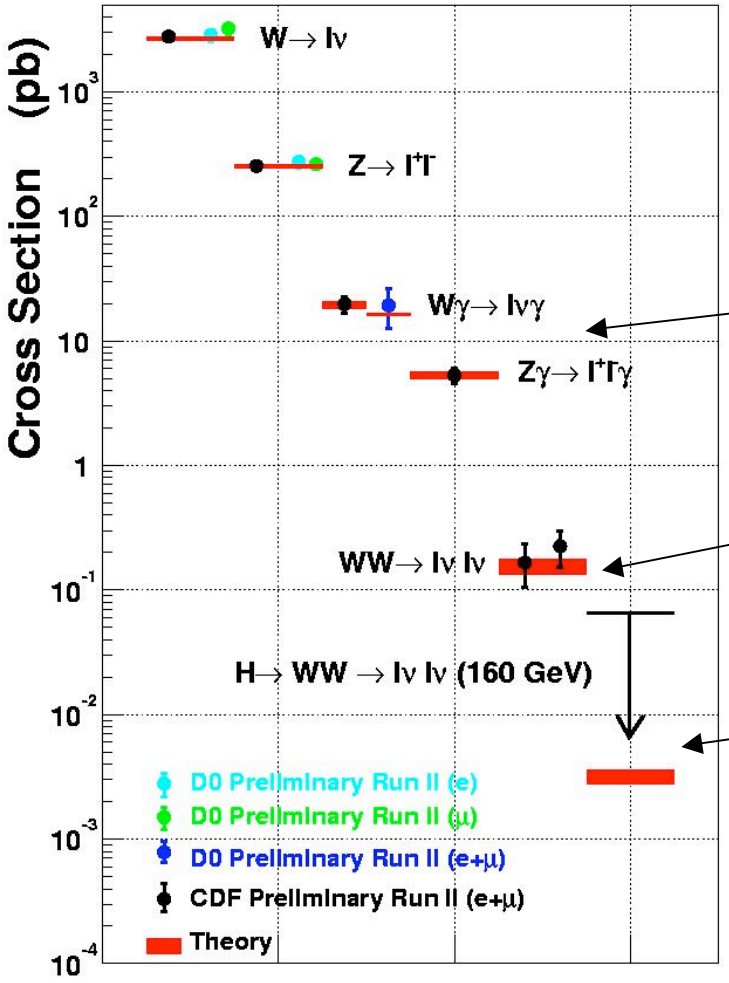
Higgs Final State Signatures



WH →WWW ➡ Like Sign Leptons + Met

H → WW ➡ Opp Sign Lepton + Met

Signal to Background Comparison



Simple cut based final state kinematic selection not sensitive

$$\frac{S}{\sqrt{B}} \approx 20$$

$$\frac{S}{\sqrt{B}} \approx 5$$

$$\frac{S}{\sqrt{B}} \approx 0.05$$

Need to optimize detector and multivariate analyses to enhance Higgs signal

ICHEP 2006 DØ Preliminary

(When we were kinda smart)

Channel	m_H	$\sigma(lim)/\sigma(SM)$	Lumi (pb^{-1})
$ZH \rightarrow \nu\nu b\bar{b}$	115	41	261
$WH \rightarrow l\nu b\bar{b}$	115	25	378
$ZH \rightarrow llb\bar{b}$	115	75	320/389
$H \rightarrow WW$	160	4	950
$WH \rightarrow WWW$	140	60	370

ICHEP 2006 Preliminary

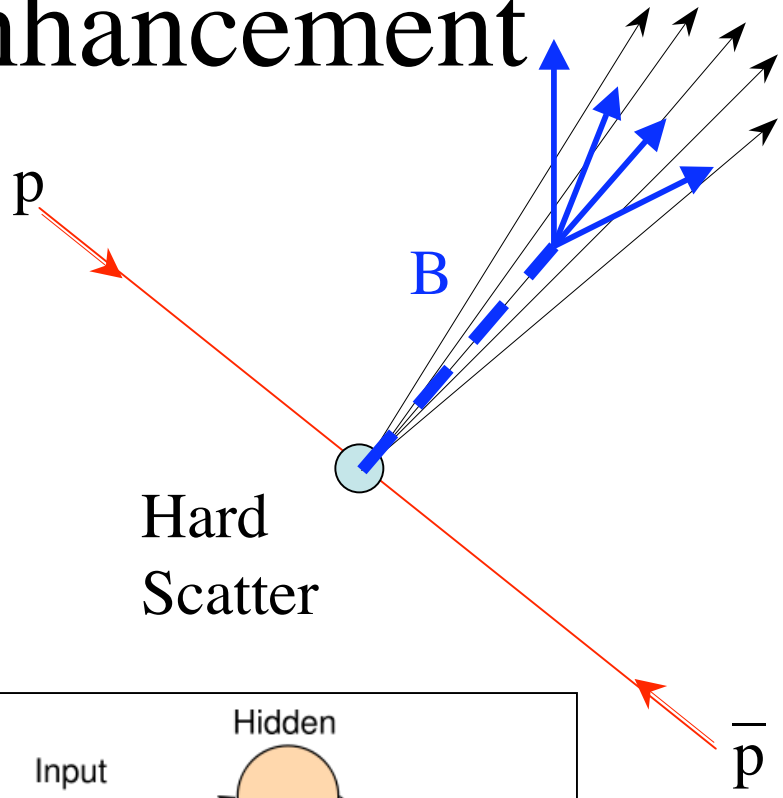
(When we were kinda smart)

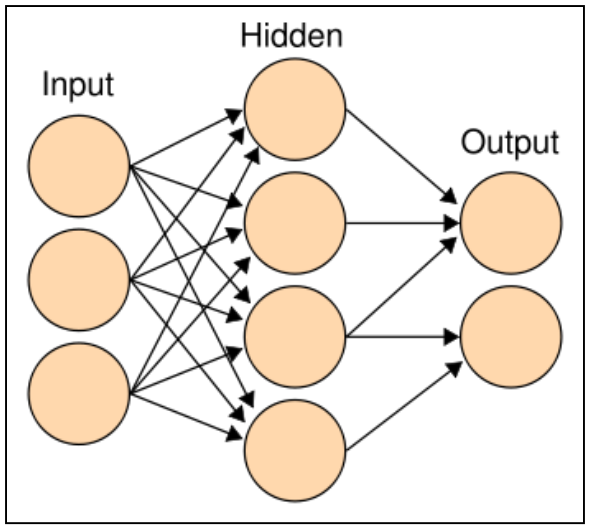
Channel	m_H	$\sigma(lim)/\sigma(SM)$	Lumi (pb^{-1})
$ZH \rightarrow \nu\nu b\bar{b}$	115	41	261
$WH \rightarrow l\nu b\bar{b}$	115	25	378
$ZH \rightarrow llb\bar{b}$	115	75	320/389
$H \rightarrow WW$	160	4	950
$WH \rightarrow WWW$	140	60	370

Scale by Luminosity and after 8 pb^{-1}, still 1.4 times SM

Higgs Signal Enhancement

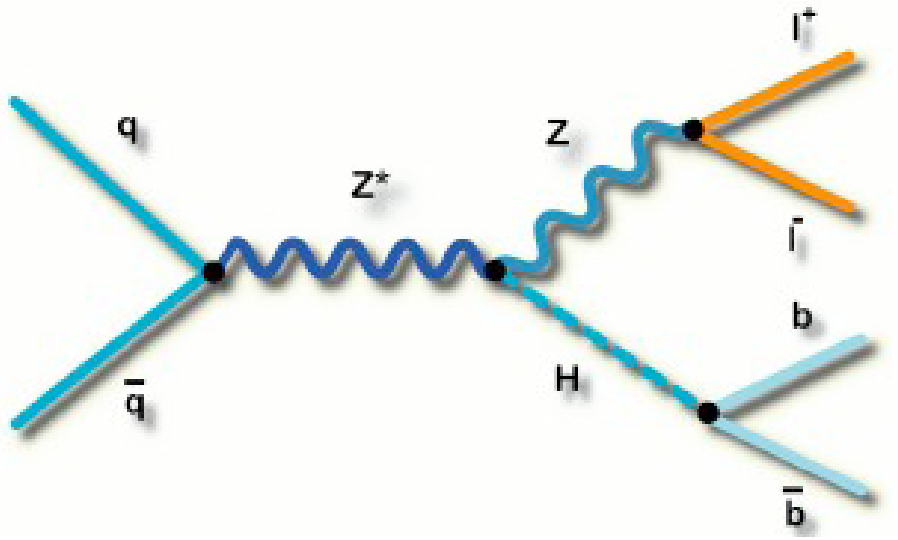
- b quark identification in detector
  - Low Mass Higgs decays with BR($b\bar{b}$) >80%
  - Silicon Vertex Detectors
- Multivariate Analysis Tools
  - Artificial Neural Nets
  - Boosted Decisions Trees
  - Matrix Element Analyses
- Combination of channels
- Combination with CDF





ZH → $ll b\bar{b}$ Signature

- Trigger on High P_T lepton (e or μ)
- Tight M(ll) selection removes BKG
- Two High P_T Jets
  - 1 tight b-tag sample
  - 2 Loose b-tag sample

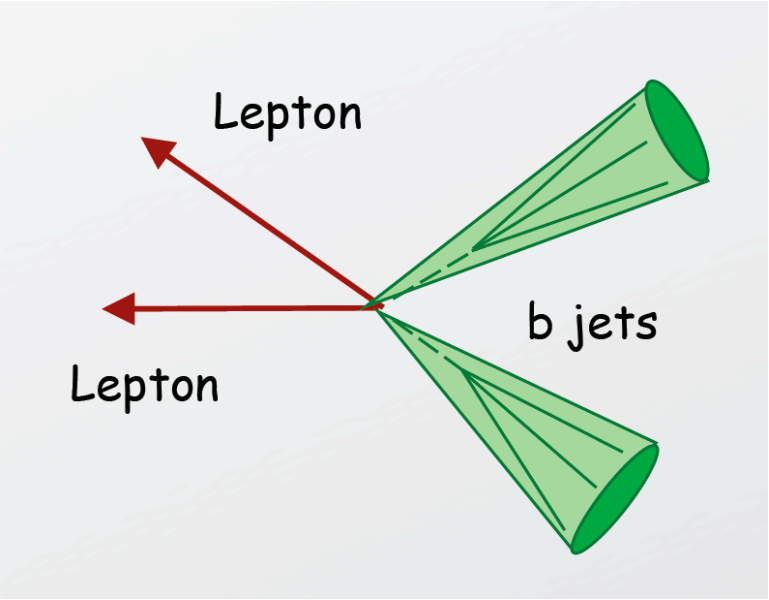


- Backgrounds
  - Z+jets
  - Z+heavy flavor
  - WZ,ZZ,ttbar
  - fake jets

- Low $P_T(l)$ threshold improves acceptance
- Kinematically constrained
- Optimum use of multivariate techniques

$ZH \rightarrow ll b\bar{b}$ Signature

- Trigger on High P_T lepton (e or μ)
- Tight M(ll) selection removes BKG
- Two High P_T Jets
  - 1 tight b-tag sample
  - 2 Loose b-tag sample

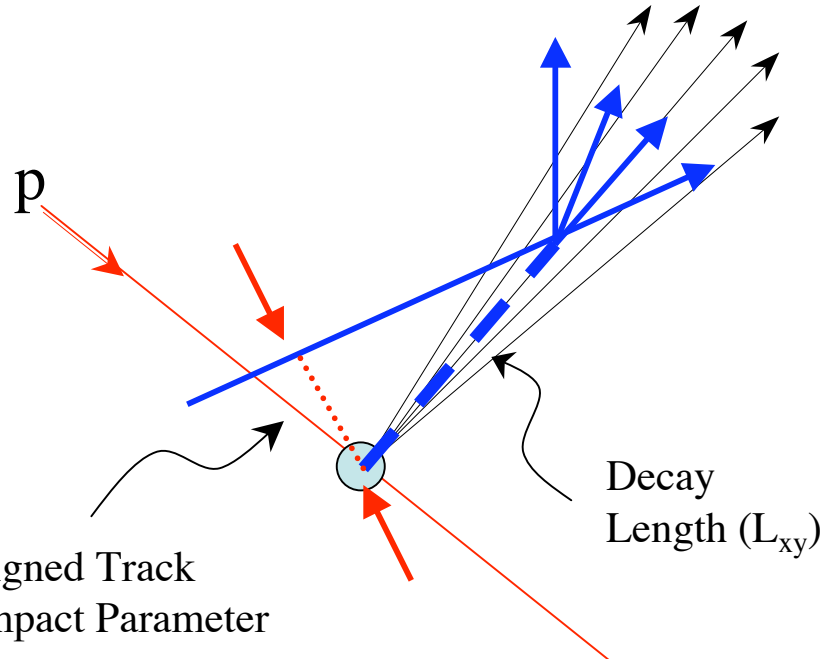


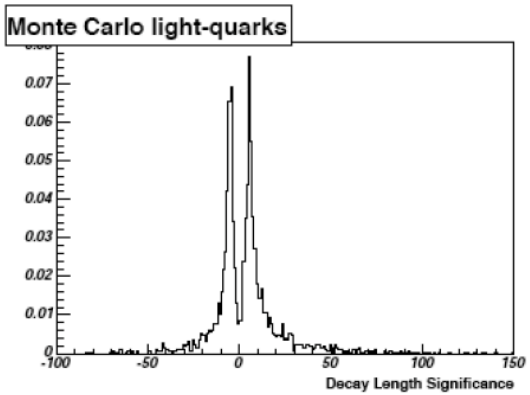
- Backgrounds
  - Z+jets
  - Z+heavy flavor
  - WZ,ZZ,ttbar
  - fake jets

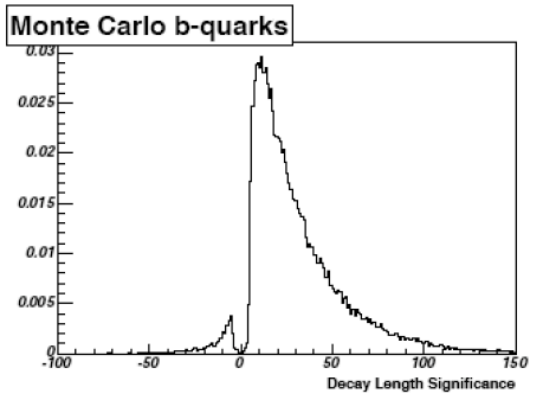
- Low $P_T(l)$ threshold improves acceptance
- Kinematically constrained
- Optimum use of multivariate techniques

b-tagging Algorithms

- Exploit b-lifetime
- Counting Signed Impact Parameter (CSIP)
- Jet Lifetime IP (JLIP)
- Secondary Vertex (SVT)
  - Build up Vertices with high S(IP)
  - $S(L_{xy}) = L_{xy}/\sigma(L_{xy})$

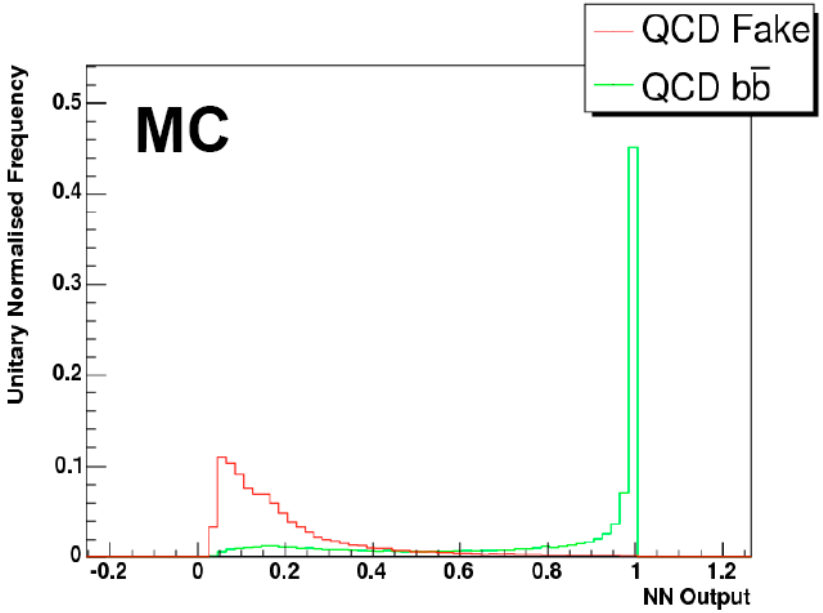






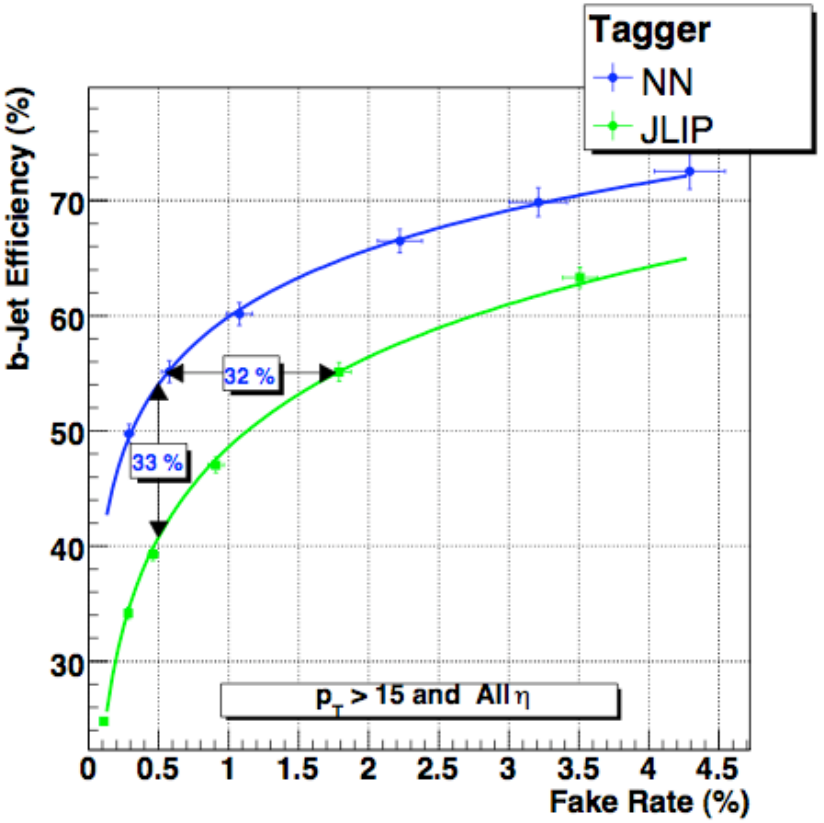
b-tagging Optimization

- Combine 7 Lifetime Variables ANN
- Multiple Operating Points
  - 50% eff @ 0.5% fake
  - 70% eff @ 4.5% fake
- Loose Double tags
- Improve b-tagging sensitivity ~30%
- Improves S/√ B ~5 in ZH analysis

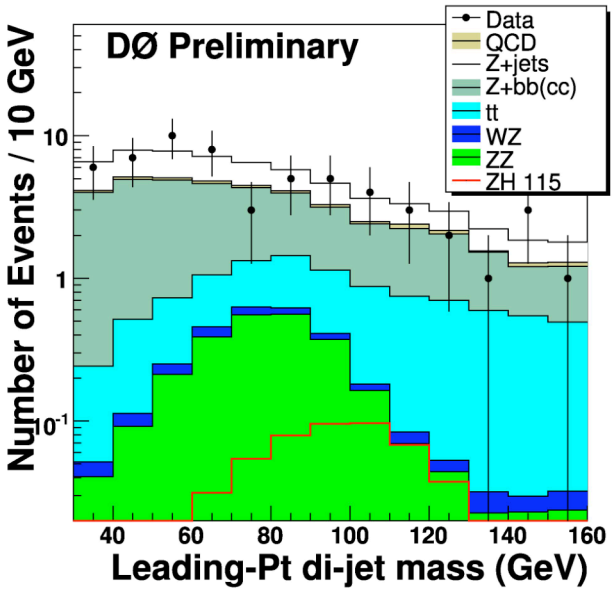


b-tagging Optimization

- Combine 7 Lifetime Variables ANN
- Multiple Operating Points
  - 50% eff @ 0.5% fake
  - 70% eff @ 4.5% fake
- Loose Double tags
- Improve b-tagging sensitivity ~30%
- Improves S/√ B ~5 in ZH analysis

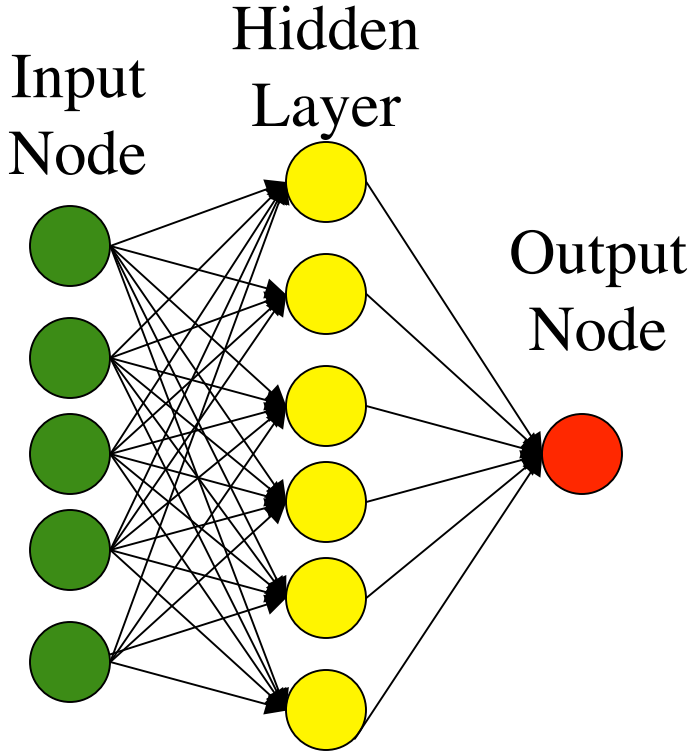


$ZH \rightarrow ll b\bar{b}$ Multivariate Analysis

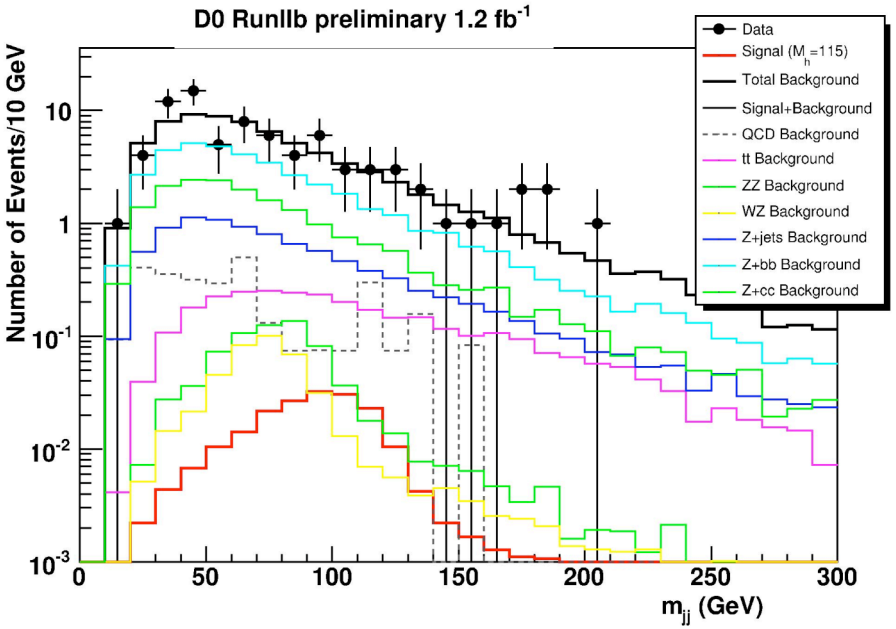


- Look for peak in M_{bb} Distribution
- Exp limit $\sigma = 4.0$ pb

- Use optimized set of variables as input to NN
- Train against EWK BG

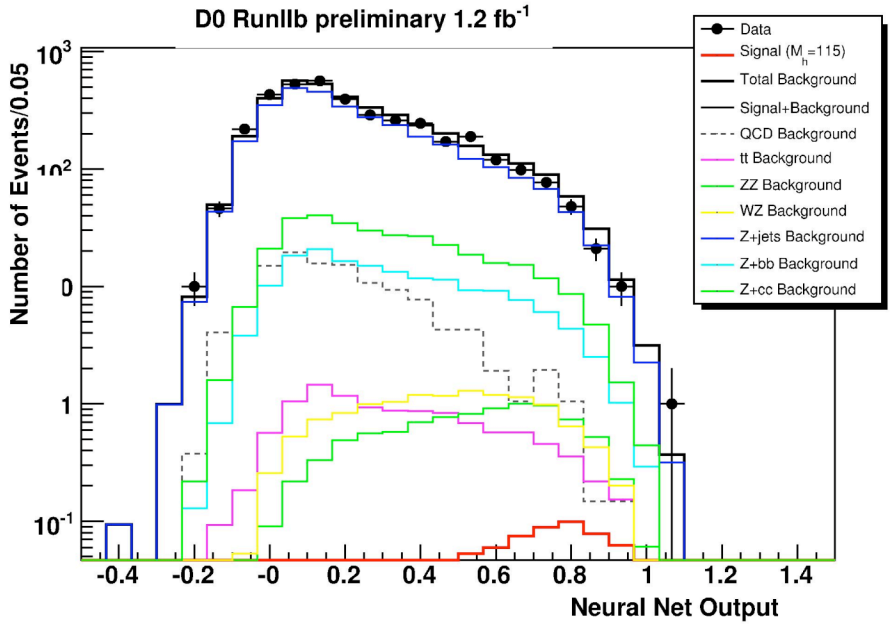


$ZH \rightarrow llb\bar{b}$ Multivariate Analysis



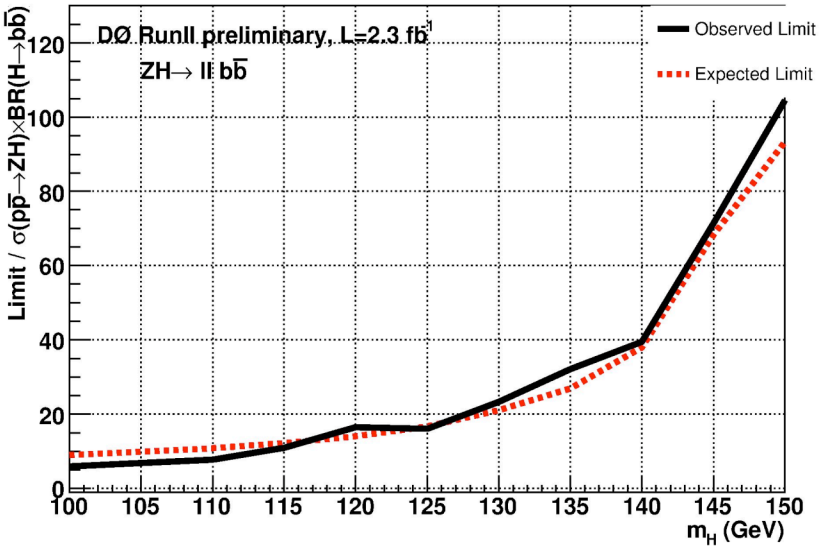
- Look for peak in M_{bb} Distribution
- Exp limit σ = 2.5 pb

- Use 10 optimized variables as input to NN
- Train against EWK BG
- Exp limit σ = 1.0 pb



$ZH \rightarrow llb\bar{b}$ Results $\int \mathcal{L} \sim 1\ fb^{-1}$

- No excess seen, set limits on $\sigma(ZH) \times Br(llb\bar{b})$



DØ limit for M_H=115 GeV

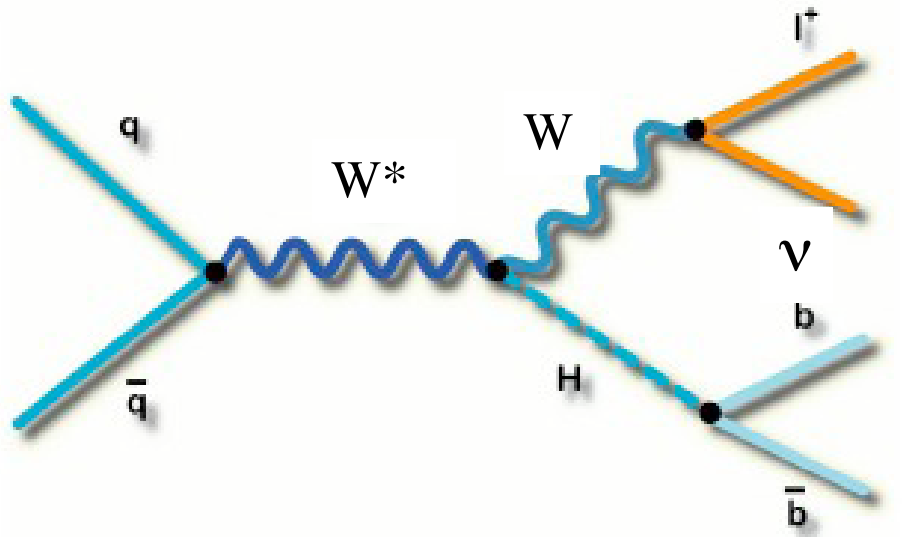
limit/SM 11 (12.3 exp)

Lumi (pb^{-1})	σ/ σ(SM)
390	75
2300	11

Improve by factor 7
Lumi factor 2.5

WH → $l\nu b\bar{b}$ Signature

- High P_T Lepton
- Large Missing Transverse Energy
- Excl 2 High P_T Jets
  - b-tag jets

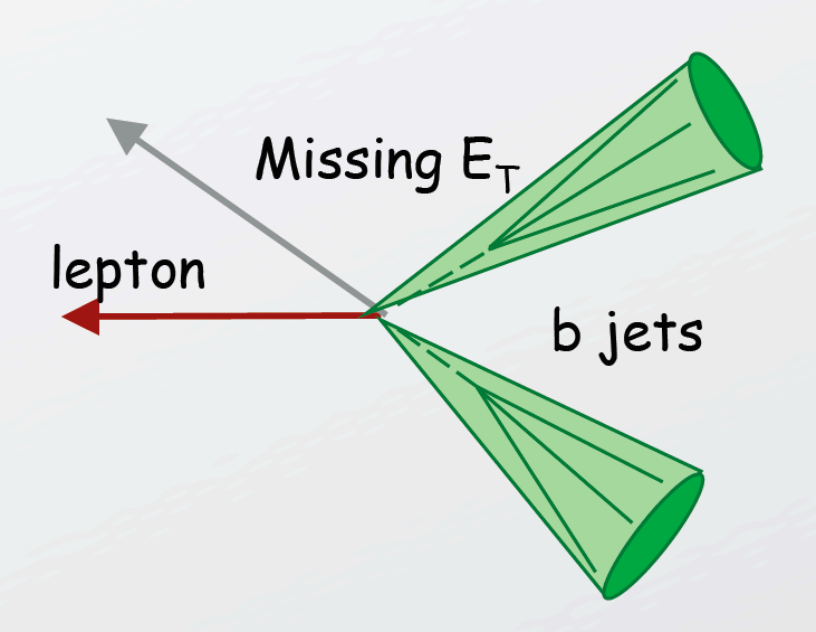


•Backgrounds
- •$Wb\bar{b}$, $Wc\bar{c}$, Wqq'
- •WW,WZ
- •top production
- •jets -> fake lepton

- Higher σ*BR
- Efficient Trigger
- Good Acceptance
- Matrix Element Analysis

WH → $l\nu b\bar{b}$ Signature

- High P_T Lepton
- Large Missing Transverse Energy
- Excl 2 High P_T Jets
  - b-tag jets

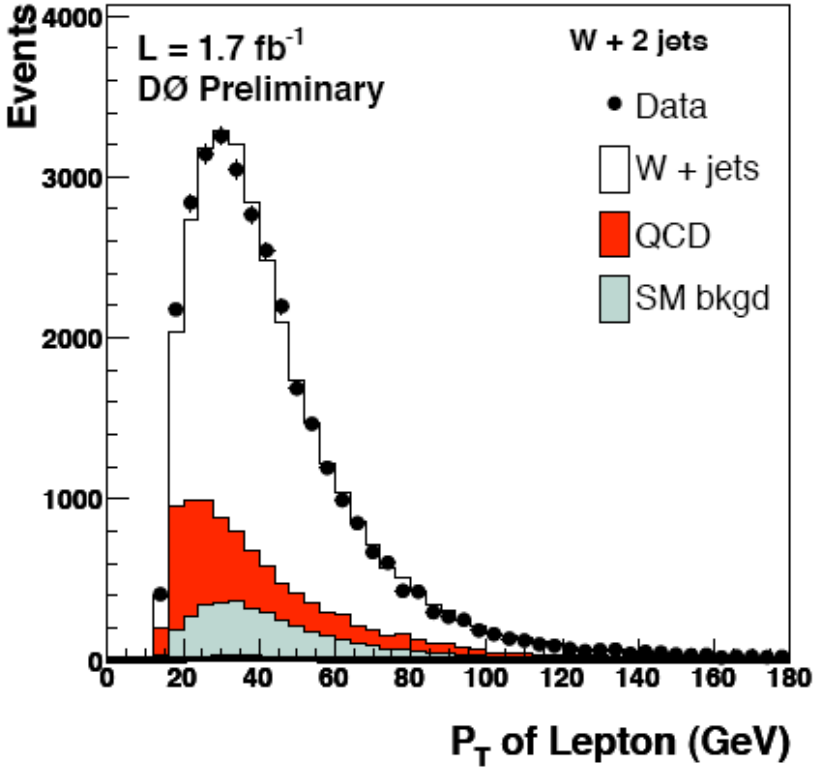


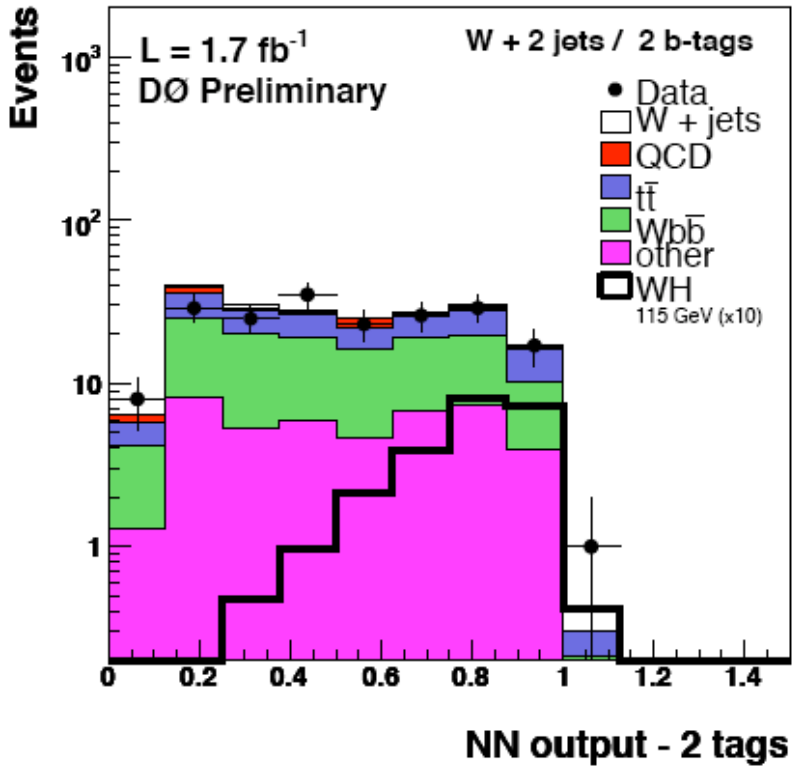
- Backgrounds
  - $Wb\bar{b}$, $Wc\bar{c}$, Wqq'
  - WW,WZ
  - top production
  - jets -> fake lepton

- Higher σ*BR
- Efficient Trigger
- Neural Net
- Matrix Element Analysis

$WH \rightarrow l\nu b\bar{b}$
Neural Net $\int \mathcal{L} \sim 1.7\ fb^{-1}$

- b-tag samples: Loose double tag, Tight single tag

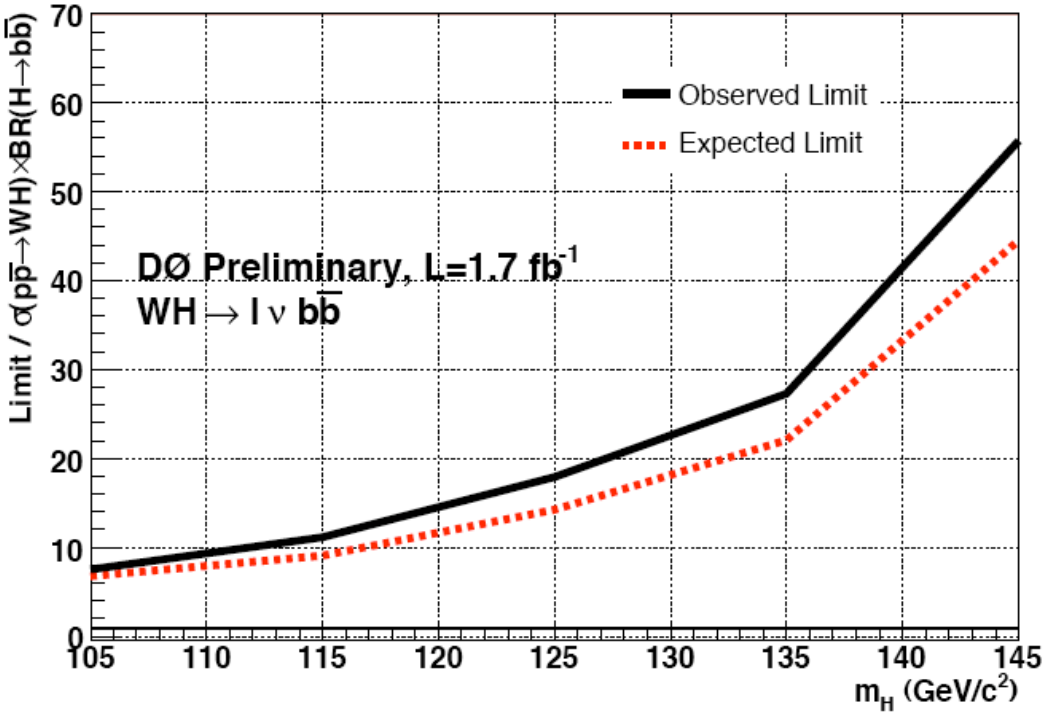




before b-tagging
335k BG - 9.9 WH

double b-tagging
204.1 BG - 2.3 WH

$WH \rightarrow l\nu b\bar{b}$
Neural Net Results



Lumi (pb^{-1})	σ/ σ(SM)
378	25
1700	9

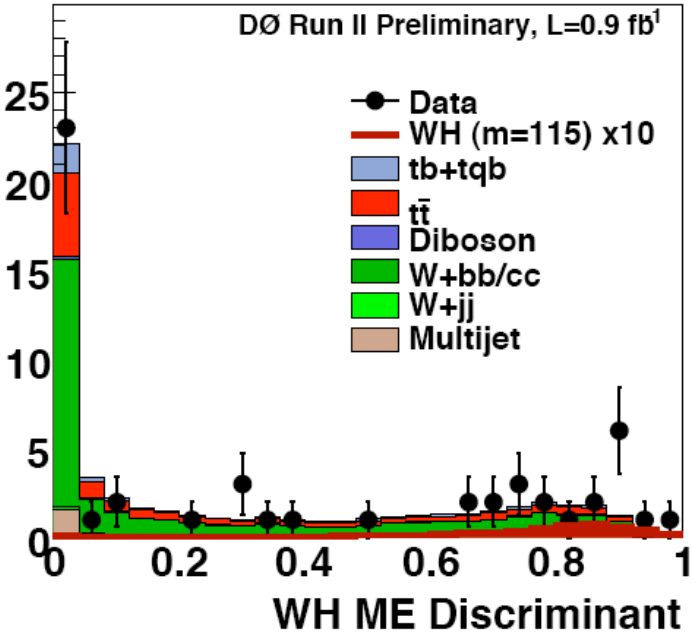
Improve by factor 3
Lumi factor 2

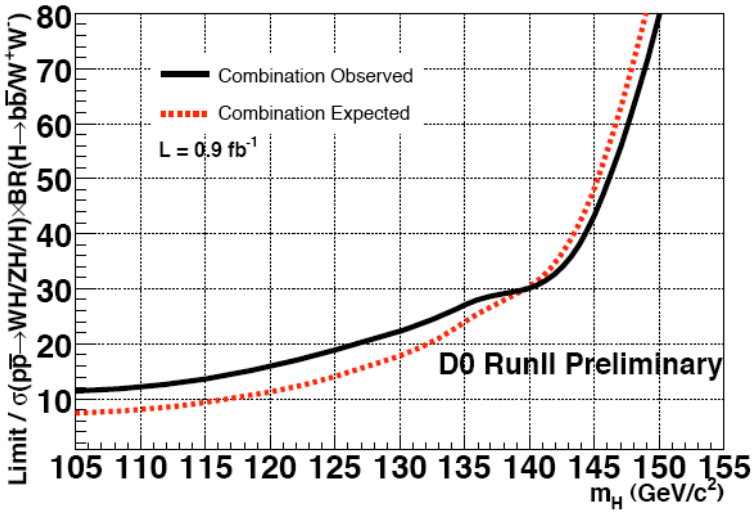
DØ limit for M_H=115 GeV

limit/SM 9.0 (11.0 exp)

$WH \rightarrow l\nu b\bar{b}$ Matrix Element $\int \mathcal{L} \sim 0.9\ fb^{-1}$

- Use LO Matrix Element to calculate probability event from WH, W+bb, W+j, etc
- Discriminant: $D_{WH}(\vec{x}) = \dfrac{P_{WH}(\vec{x})}{P_{WH}(\vec{x}) + P_B(\vec{x})}$

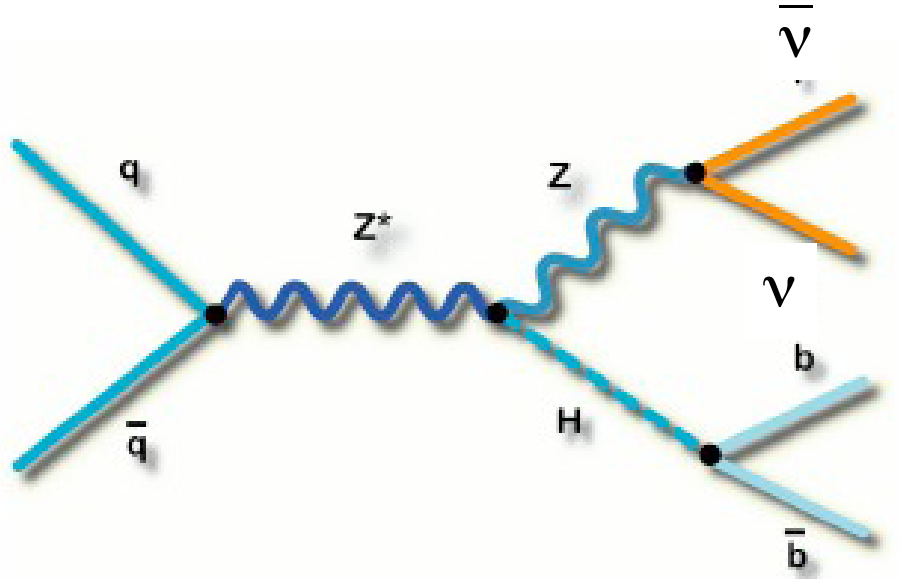




DØ limit for M_H=115 GeV limit/SM 14 (9.5 exp)

$ZH \rightarrow \nu\nu b\bar{b}$ Signature

- 2 High P_T Jets
- Large Missing Transverse Energy
- Cut on $\Delta\phi$ between jets and Missing E_T
- Calorimeter and Track based discriminants

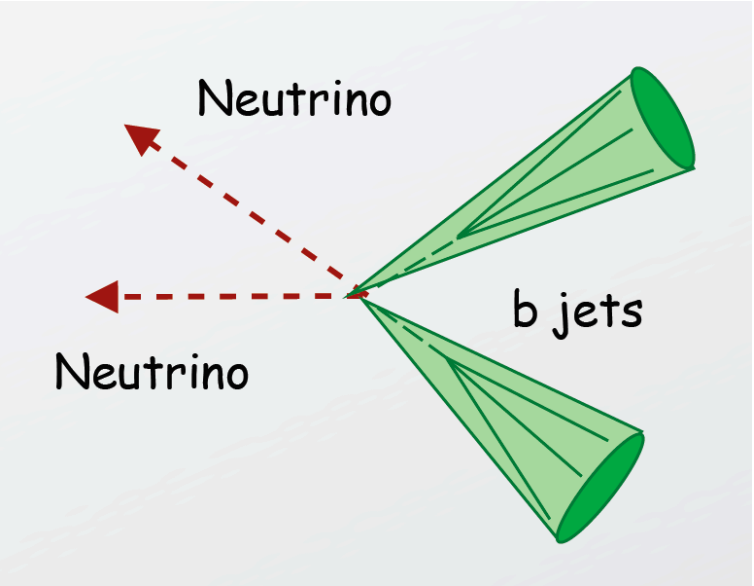


- Backgrounds
  - Multijet Backgound
  - W/Z$b\bar{b}$, Z$c\bar{c}$, Zqq'
  - WW,WZ,ZZ
  - tt, single top

- Highest σ*BR
- Consider WH w/ missing lepton signal
- Feed kinematics into Boosted Decision Tree

$ZH \rightarrow \nu\nu b\bar{b}$ Signature

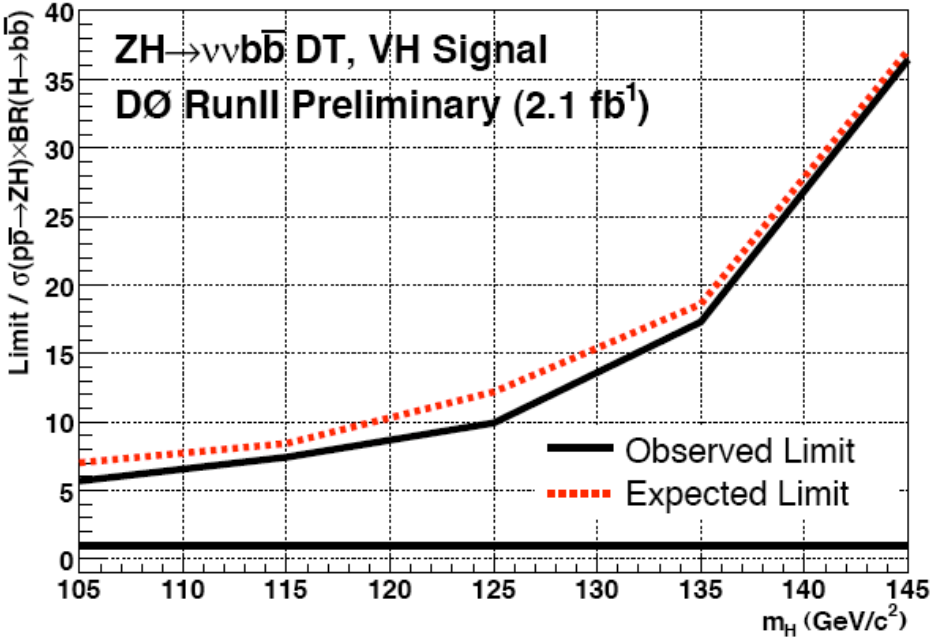
- 2 High P_T Jets
- Large Missing Transverse Energy
- Cut on $\Delta\phi$ between jets and Missing E_T
- Calorimeter and Track based discriminants



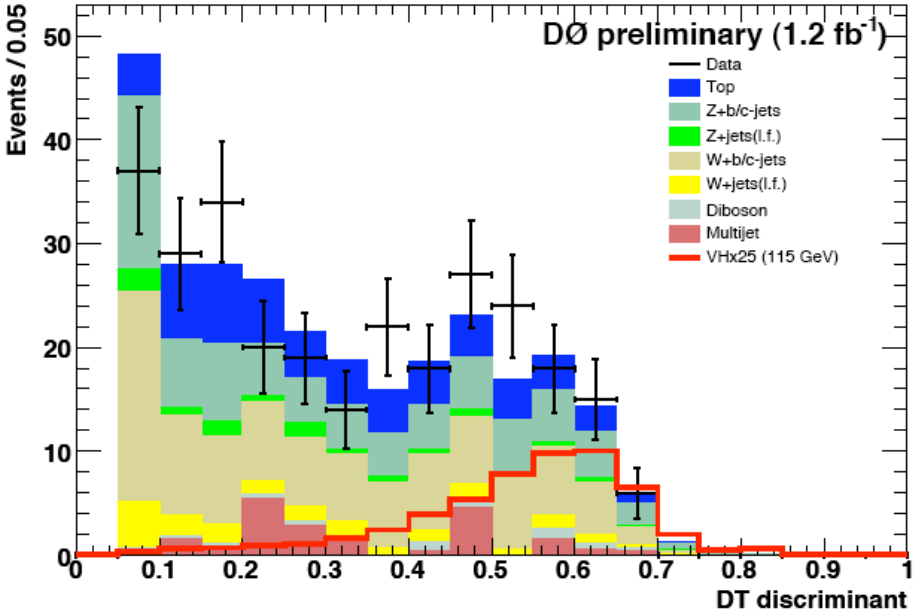
- Backgrounds
  - Multijet Backgound
  - $W/Zb\bar{b}$, $Zc\bar{c}$, Zqq'
  - WW,WZ,ZZ
  - tt, single top

- Highest σ*BR
- Consider WH w/ missing lepton signal
- Feed kinematics into Boosted Decision Tree

$ZH \rightarrow \nu\nu b\bar{b}$
Neural Net Results

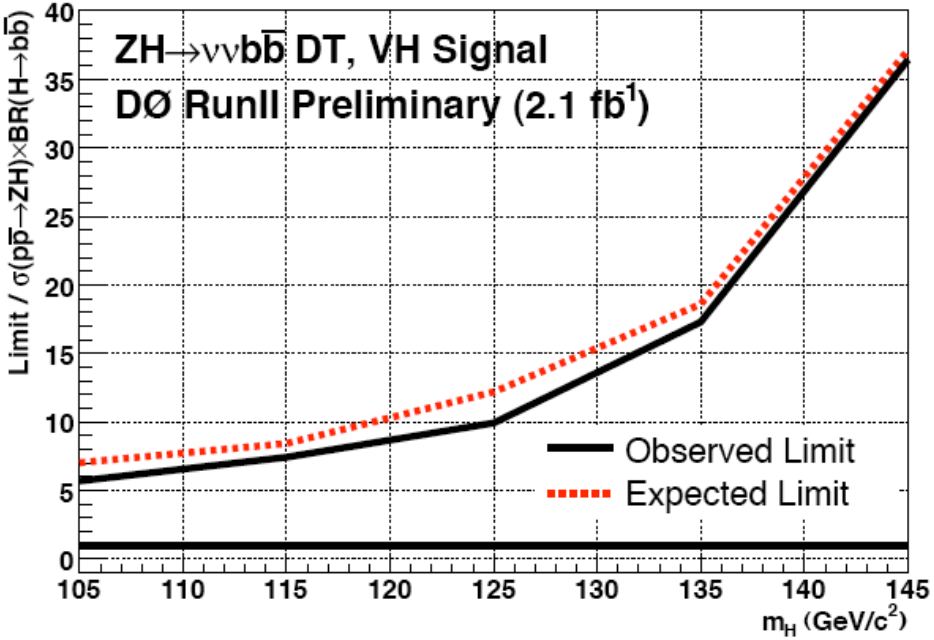


DØ limit for M_H=115 GeV
limit/SM 7.5 (8.4 exp)



Good agreement in double tag BDT discriminant

$ZH \rightarrow \nu\nu b\bar{b}$ Neural Net Results



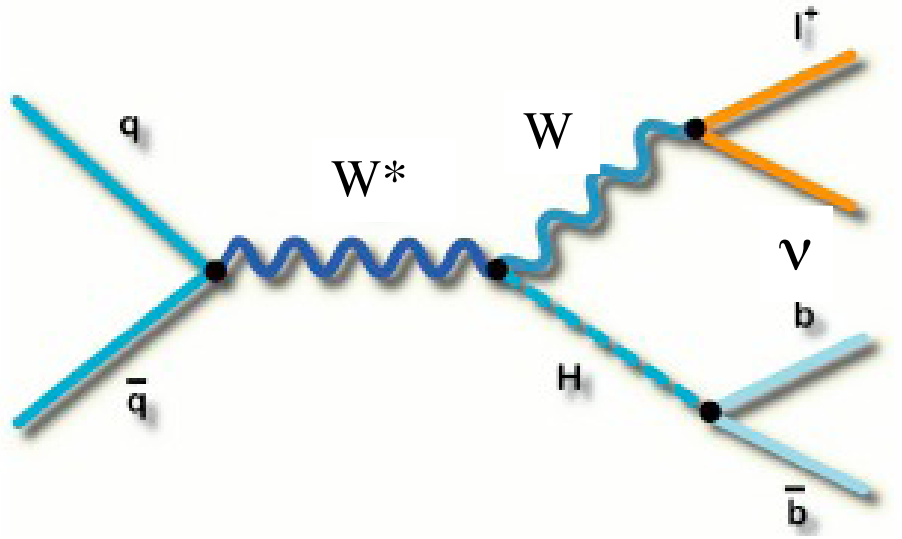
DØ limit for M_H=115 GeV
limit/SM 7.5 (8.4 exp)

Lumi (pb^{-1})	σ/ σ(SM)
261	41
2100	7.5

Improve by factor 5.5
Lumi factor 2.8

Can the Tevatron measure WV?

- High P_T Lepton
- Large Missing Transverse Energy
- Excl 2 High P_T Jets
  - b-tag jets

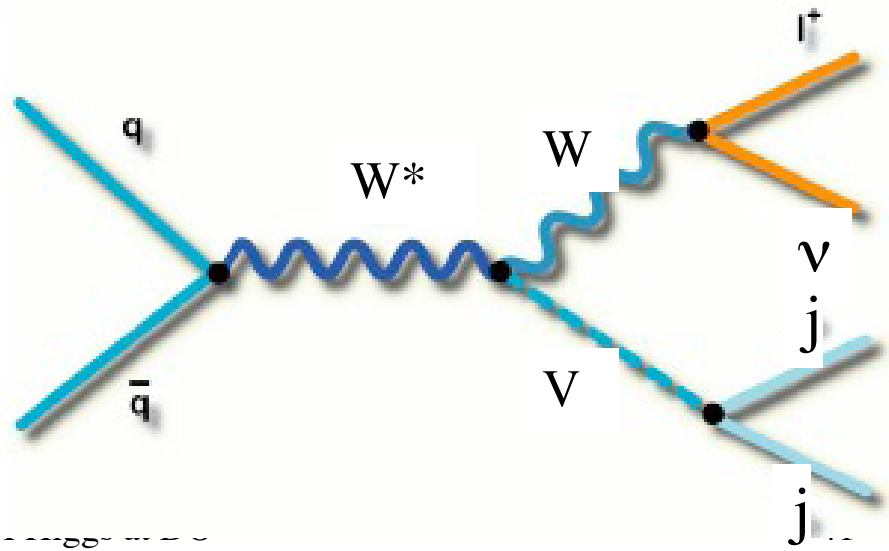


•High P_T Lepton

•Large Missing Transverse Energy

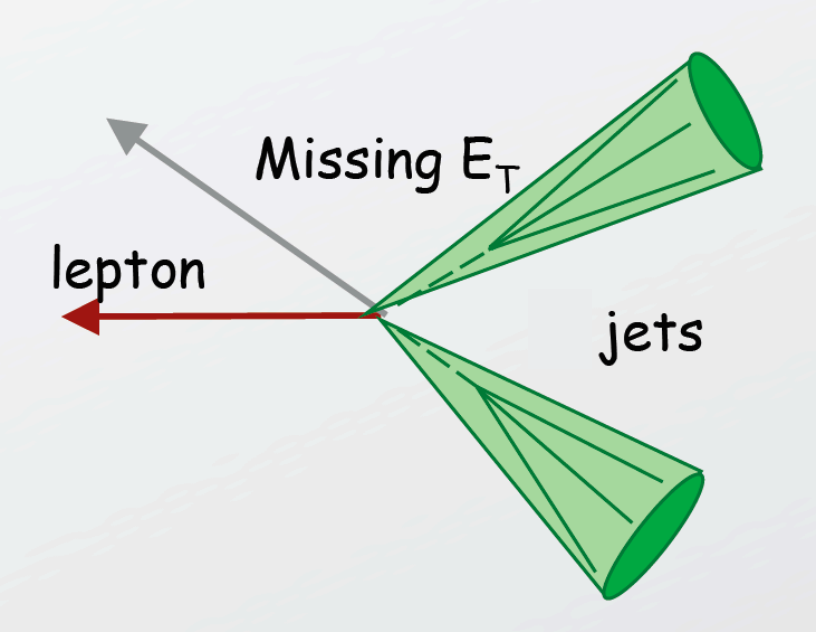
•Excl 2 High P_T Jets

•3x greater cross section



WV → *lνqq* Signature

- High P_T Lepton
- Large Missing Transverse Energy
- >= 2 High P_T Jets



- Backgrounds
  - $W b\bar{b}$, $W c\bar{c}$, Wqq'
  - $Z b\bar{b}$, $Z c\bar{c}$, Zqq'
  - top production
  - jets -> fake lepton

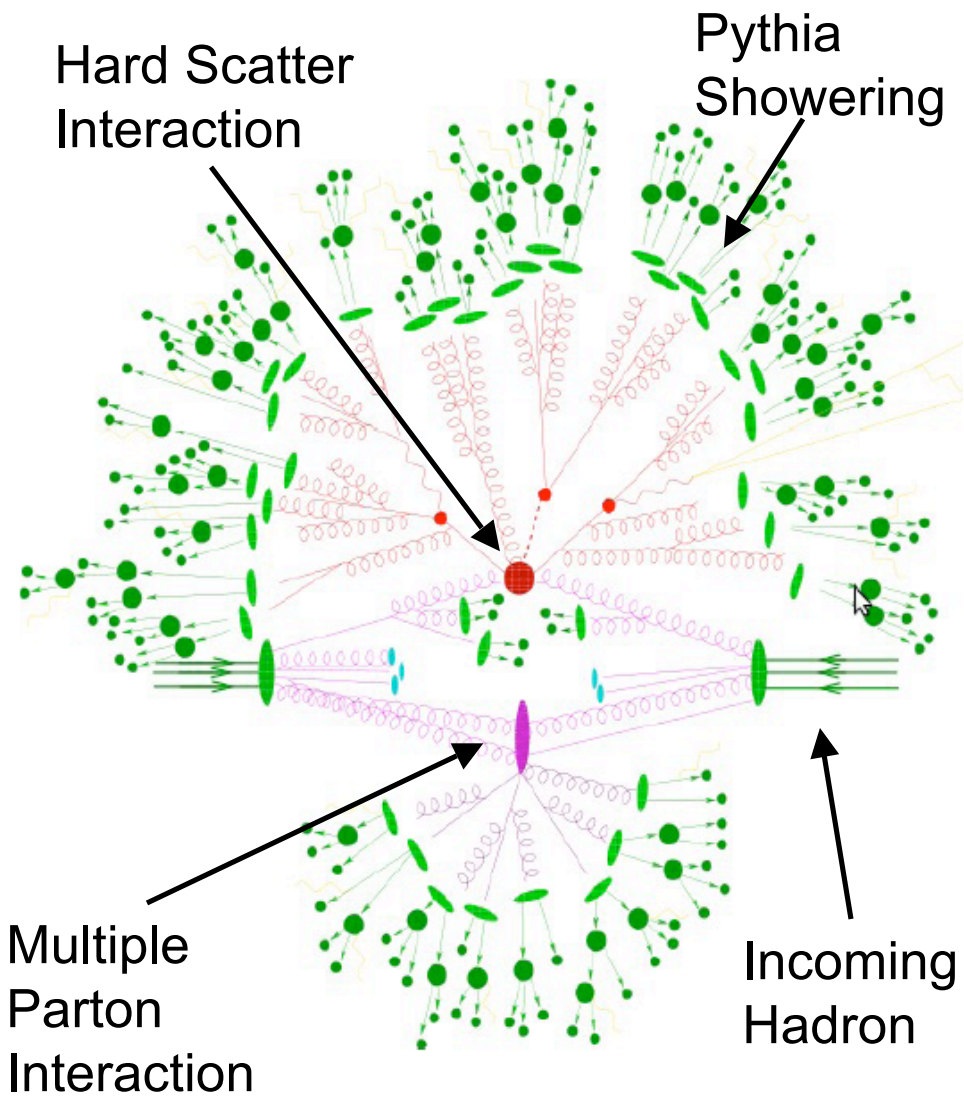
- Transverse Mass

$$M_T^W = \sqrt{2\, p_T(l^{\pm})\, p_T(\nu)\, (1-\cos(\phi(l^{\pm})-\phi(\nu)))}$$

- W/Z dijet peak indistinguishable

Improved Generator Modeling

- Monte Carlo Generators rely heavily on phenomenological models
  - limited number of Feynman diagrams
  - limited knobs to tune
- Dominant productino varies (QCD vs EWK)
- Tuning limited phase space does not guarantee global agreement
  - Unknown correlations
  - flavour content, fragementation
  - avoid over-tuning

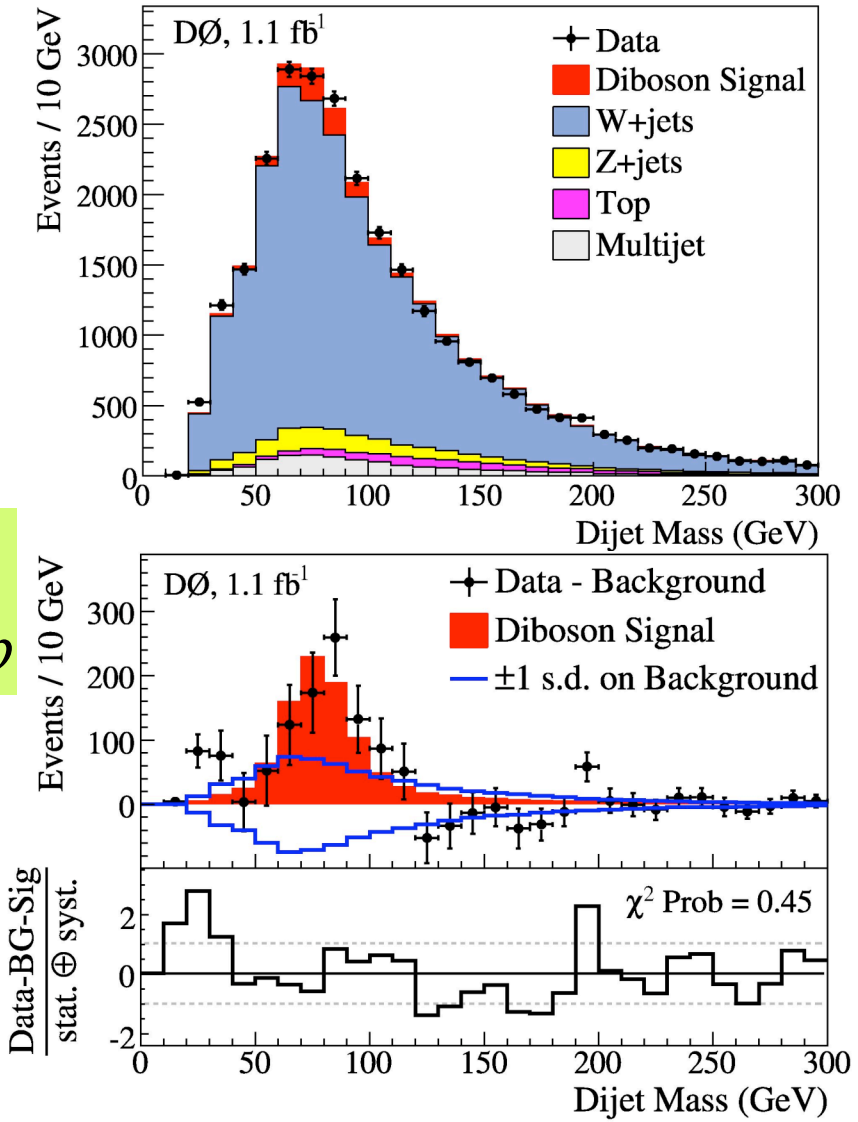


WV → *lνqq* Results

- Using only the dijet mass for discrimination
- See an excess and measure cross section

$$\sigma(WW + WZ) =$$
$$18.5 \pm 2.8(stat) \pm 4.9(syst) \pm 1.1(lumi)\,pb$$

- 3.3 σ obs over bkg



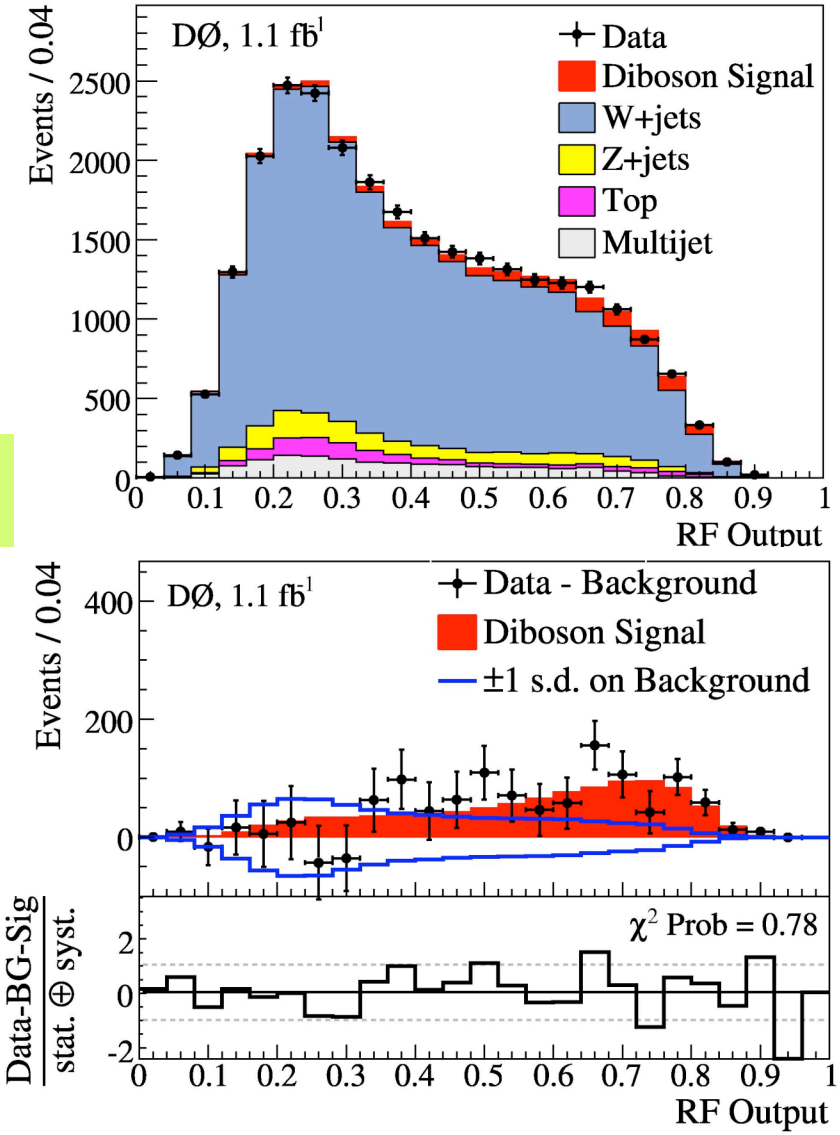
WV → *lνqq* Results

- Construct Random Forest of Decision Trees
- Increase Sensitivity by 32%

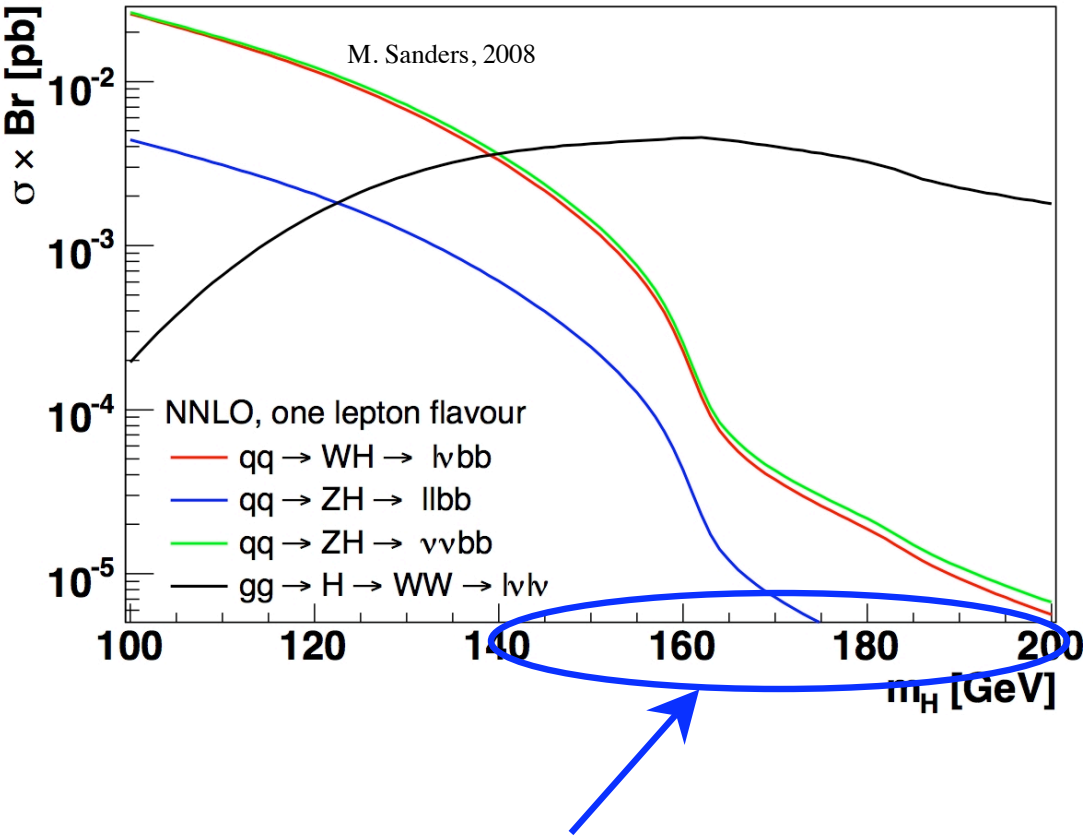
$$\sigma(WW + WZ) =$$

$$20.2 \pm 2.5(stat) \pm 3.6(syst) \pm 1.1(lumi)\,pb$$

- 4.4 σ obs over bkg
- Major step on the road to Higgs discovery



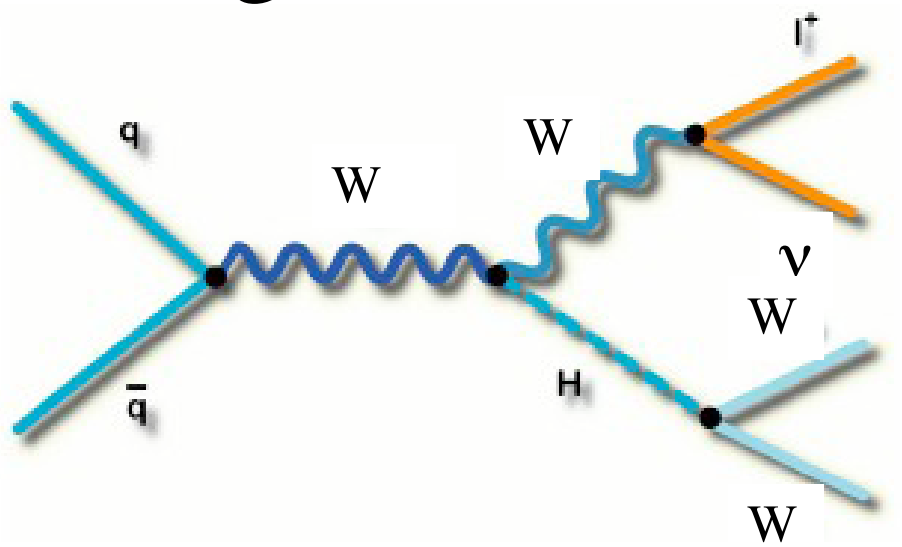
Higgs Final State Signatures



High Mass Higgs →(140,190)

WH→WWW* Signature

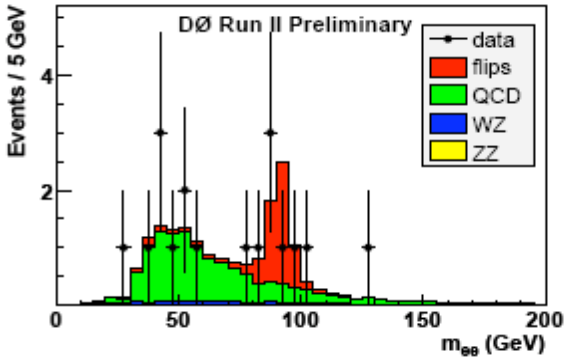
- 2 Like Sign High P_T Leptons
- ee, μμ, and eμ

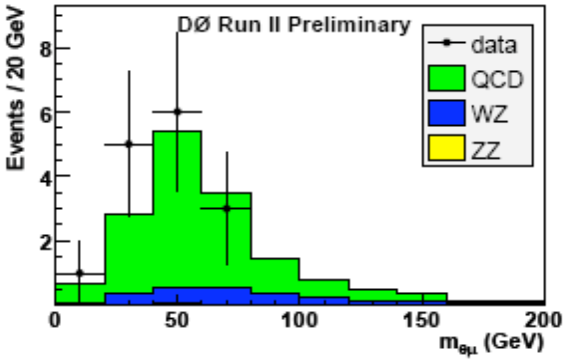


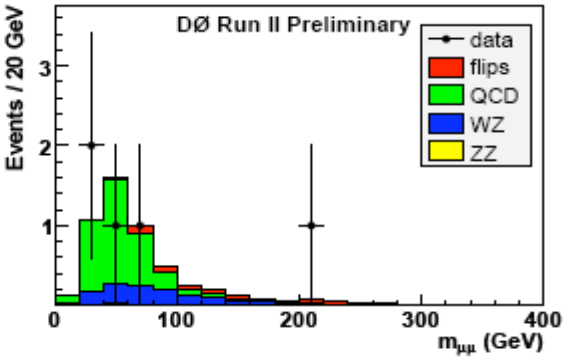
- Backgrounds
  - WW,WZ
  - Charge flips Drell-Yan
  - QCD

- Low σ*BR
- Important for m_H 125-145
- Determine QCD and Charge flips from data

WH→WWW* Signature



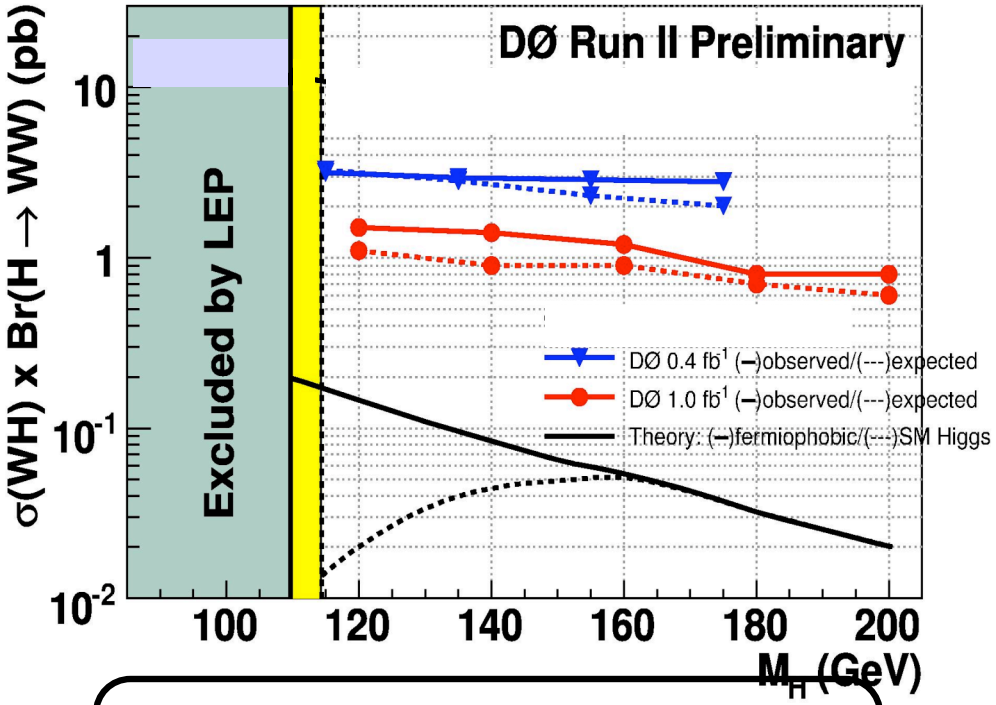




	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
$WZ \rightarrow l\nu ll$	1.18±0.17	2.46±0.34	1.29±0.18
$ZZ \rightarrow llll$	0.10±0.01	0.16±0.02	0.07±0.01
QCD	7.4±1.1	15.4±2.8	2.8±0.9
flips	11.9±3.8	0.04±0.02	0.8+2.3−0.8
total	20.6±4.0	18.0±2.8	5.0+2.5−1.2
Data (Signal@ 160 GeV)	**19 (0.10)**	**15 (0.21)**	**5 (0.11)**

➔ **Topological Likelihood discriminant, built on 3 variables per channel (E_T^{miss}, $\Delta\phi$,'s)**

WH→WWW* Signature



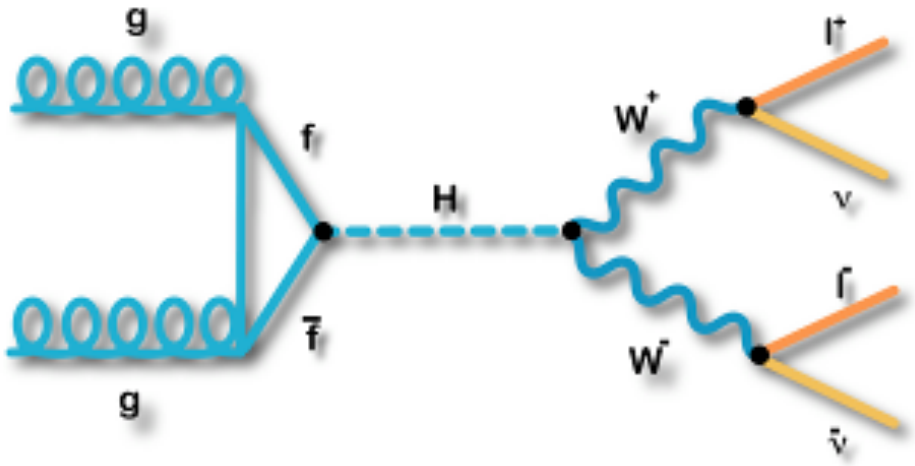
DØ limit for M_H=140 GeV
limit/SM 24 (20 exp)

Lumi (pb^{-1})	σ/ σ(SM)
370	60
1000	24

Improve by factor 2.5
Lumi factor 1.6

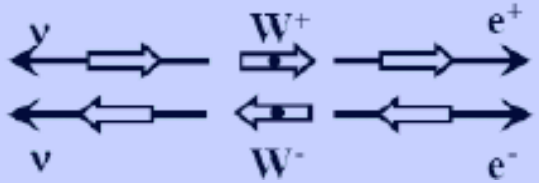
H→WW→$l\nu l\nu$ Signature

- 2 High P_T Leptons
  - ee, μμ, and eμ
- Large Missing Transverse Energy
- M(*ll*) Cut



- Backgrounds
  - WW,WZ
  - Drell-Yan
  - tt, single top

- Kinematic Discriminants
  - Lepton Invariant Mass
  - *ll* Opening Angle

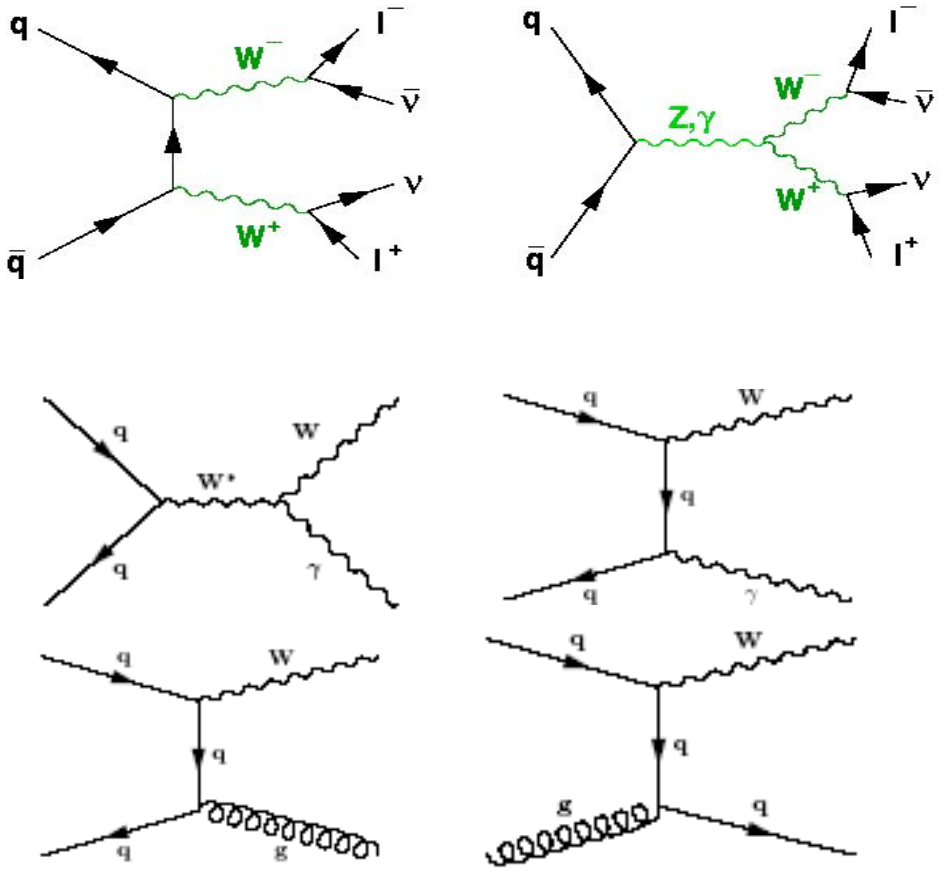


- DØ Kinematics input NN

H→WW→$l\nu l\nu$ Backgrounds

- WW/WZ
- W+Jets/γ
- Drell-Yan
- $t\bar{t}$, single top
- Multijet from like-sign sample

All cross sections have been measured by both experiments

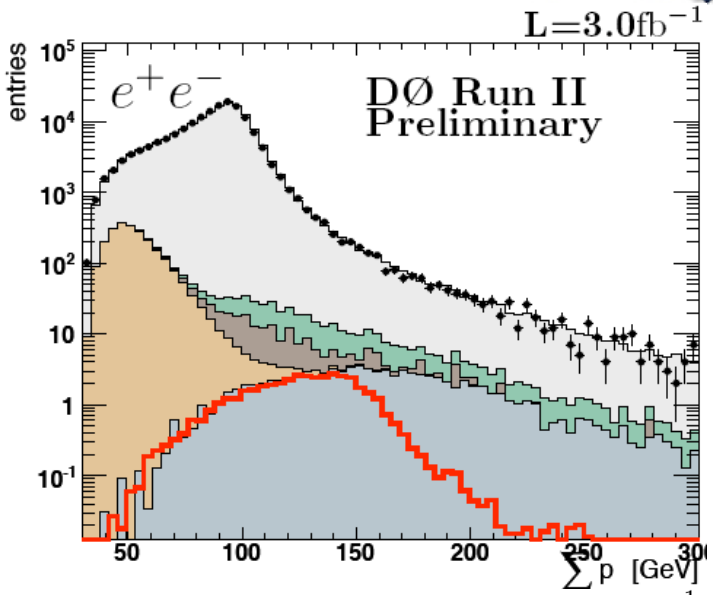


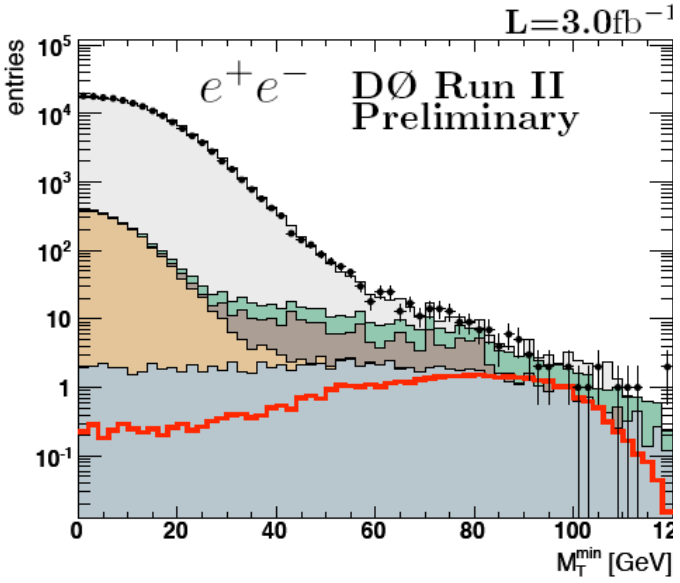
H→WW→$l\nu l\nu$ Neural Net

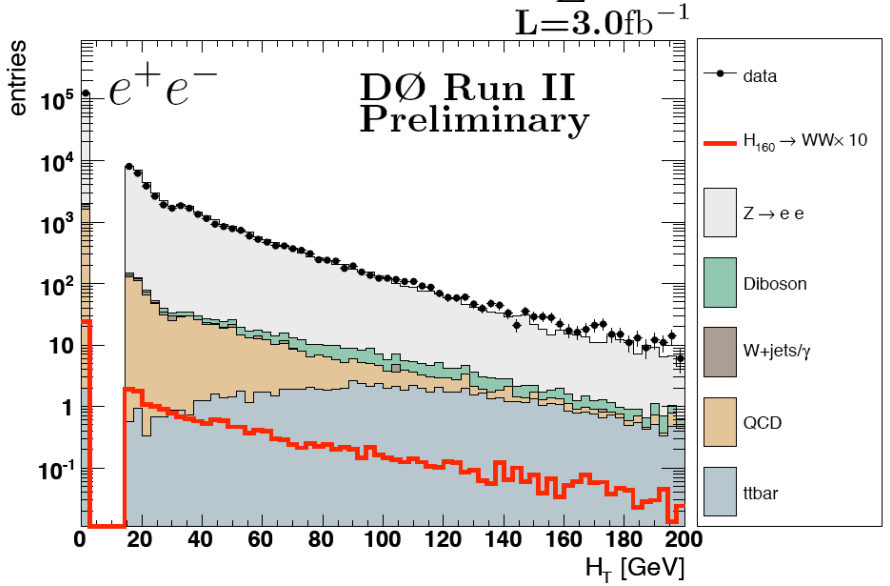
NN trained for each Higgs mass in 5 GeV steps, for each channel

Output of NN distribution used to set limits

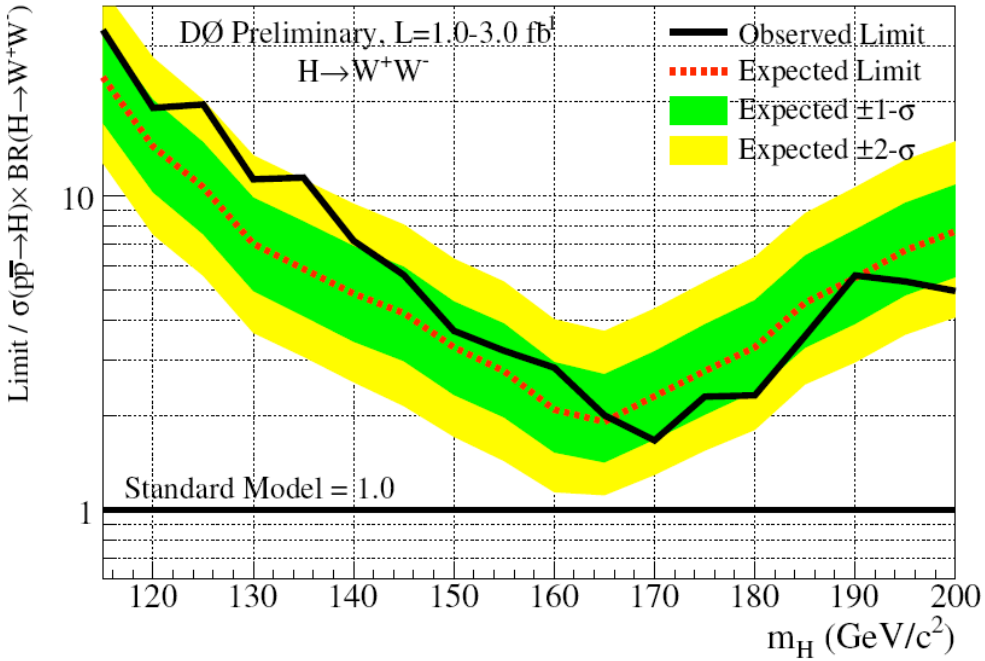
Object Variables	Event Var	Topo Var
P_T^{l1} & P_T^{l2}	$M_{inv}(l,l)$	$\Delta\phi(l,l)$
Σ lepton P_T	$M_t^{min}(1,\not{E}_T)$	$\Delta\phi(\not{E}_T,l_1)$
Σ jet P_T (H_T)	$\not{E}_T$	$\Delta\phi(\not{E}_T,l_2)$
Lepton Quality	$\not{E}_t^{scalar}$	







H→WW→$l\nu l\nu$
ME + NN Results



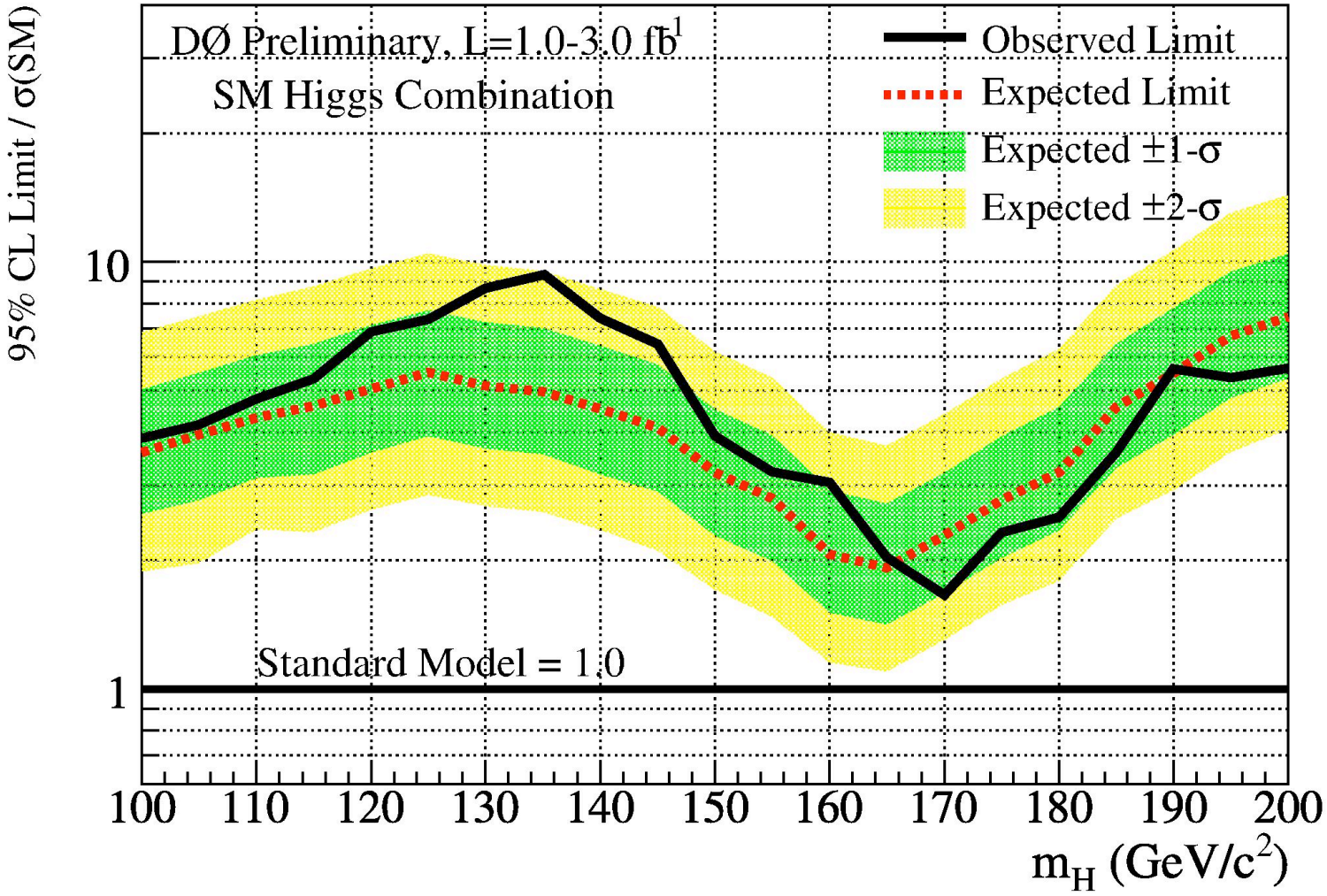
DØ limit for M_H=160 GeV

limit/SM 2.0 (1.9 exp)

Lumi (pb^{-1})	σ/ σ(SM)
950	4
3000	2.0

Improve by factor 2.0
Lumi only factor 1.6

Combined DØ SM Higgs Limits



How Smart Were We?

- Compare the limits from ICHEP 2006
- Average smartness of 1.75
- Keeping pace with expectations from 2006
- Can we keep going?

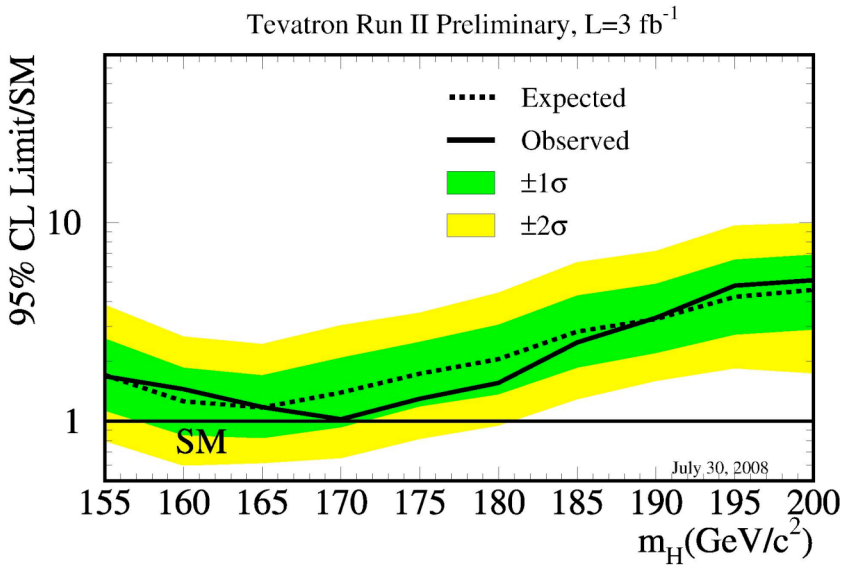
Channel	Lumi Scale	Actual Scale	Smart-ness
$\nu\nu b\bar{b}$	2.8	5.5	2.0
$l\nu b\bar{b}$	2	3	1.5
$llb\bar{b}$	2.5	6.5	2.5
WWW*	1.6	2.5	1.6
WW*	1.6	2.0	1.3

Combined Channels Limits

- Work to combine all recent results still in progress

http://arxiv.org/abs/0712.2383

Combined	CDF	DØ
WH→ lvbb	1.7 fb^{-1} (old !)	1.7 fb^{-1}
ZH→llbb	1.0 fb^{-1}	1.1 fb^{-1}
ZH→vvbb	1.7 fb^{-1}	2.3 fb^{-1}
H→WW	3.0 fb^{-1}	3.0 fb^{-1}



- CDF limits improved more than 20% for this combination
  - -10% from analysis improvements
- Started to exclude high mass Higgs !

Higgs	Obs	Exp
115	3.6	3.3
165	1.0	1.4

DØ Improvements in the Pipeline

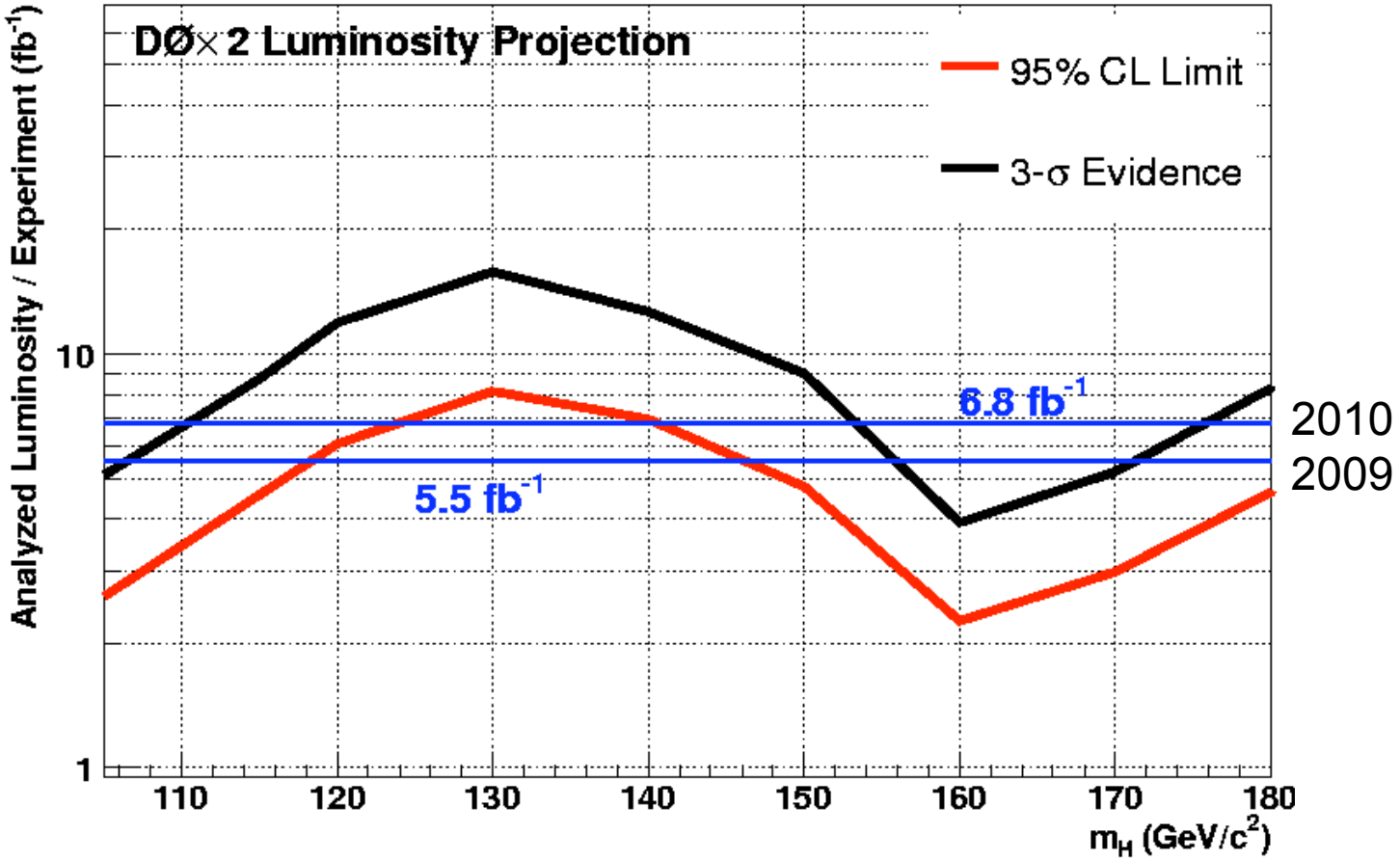
Low Mass Higgs

- ~~NN Discriminants~~
- ~~Lepton Acceptance~~
- Lepton ID (10%)
  - EM Identification
  - Isolated Track
- b-tagging w/ L0 (10%)
- dijet mass reso. (15%)
- Extend ME (20%)
- Expect 2.0 by 2010

High Mass Higgs

- ~~NN Discriminants~~
- ~~Lepton Acceptance~~
- Lepton ID (10%)
  - EM Identification
  - Isolated Track
  - tau channels
- Extend ME and other Multivariate Techniques (30%)
- Expect 1.4 by 2010

Tevatron Projections



- Assumes two experiments and analysis improvements (2.0 and 1.4)

Summary

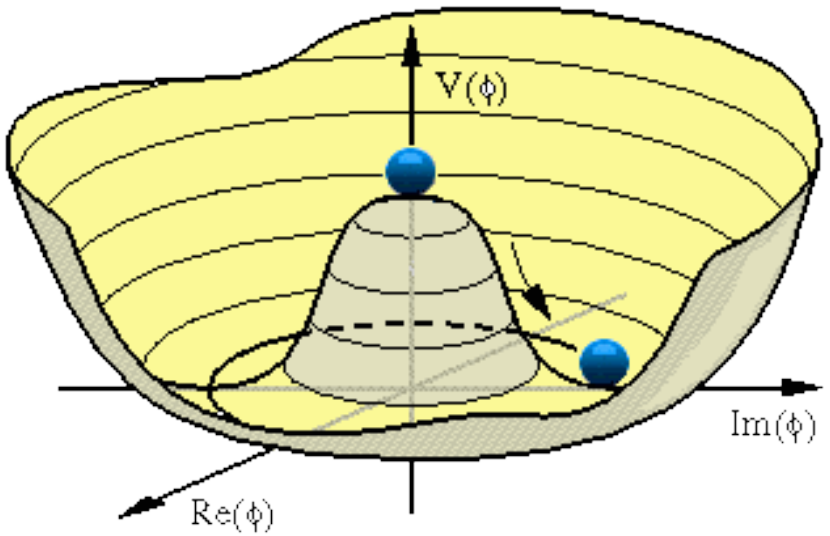
- The Search continues, but the pieces are coming together.
- Tevatron analyses will continue to improve faster than luminosity
  - Jet Energy Scale, Dijet invariant mass resolution, b-tagging
  - Incorporate advanced techniques in all analyses
  - Improved lepton identificaion
- Tevatron excluded a 170 GeV SM Higgs @ 95% CL and will continue to expand excluded range
- Potential is there for 3σ evidence with 2010 operation

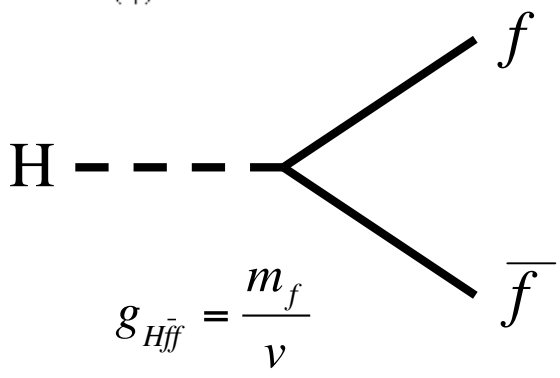
Backup

SM Higgs Mechanism

- Adding explicit mass terms violates gauge invariance and renorm.
- Add complex doublet of scalar fields $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$
- Symmetry breaking occurs at υ=246 GeV
- Generates massive gauge field (W^+,W^-,Z)
- Fermion couplings generates particle masses
- But no prediction of m_H…

$$V = -\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

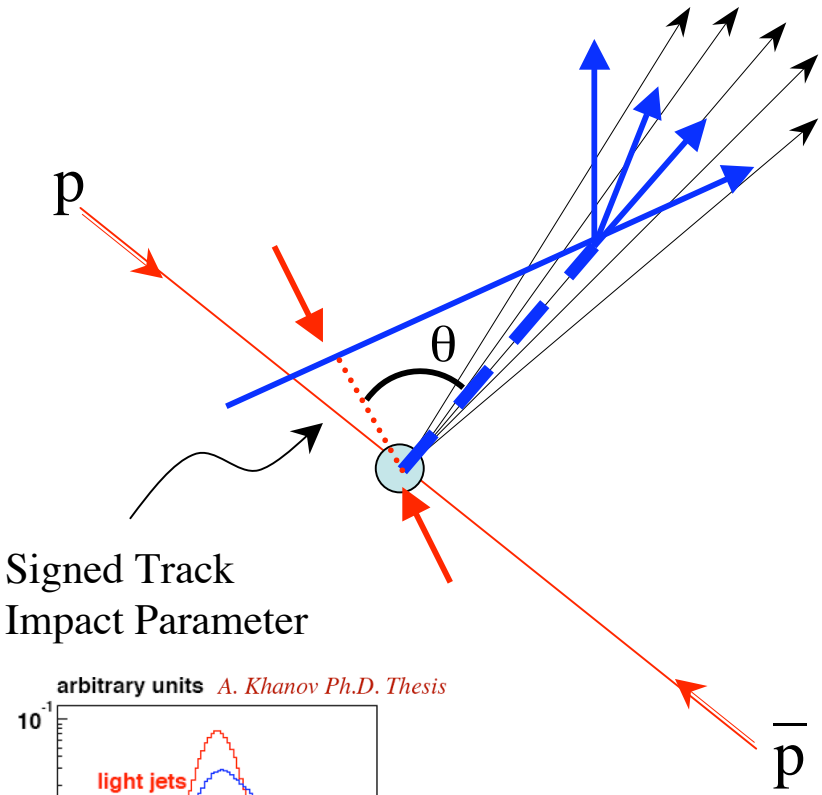


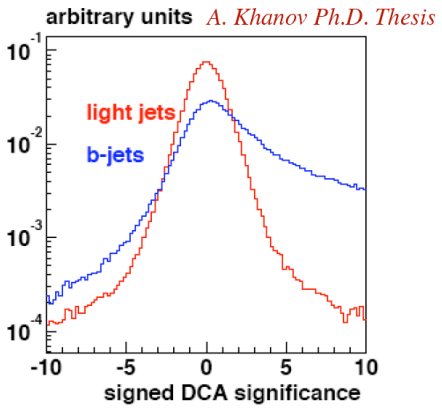


$$g_{H\bar{f}f} = \frac{m_f}{v}$$

b-tagging Algorithms

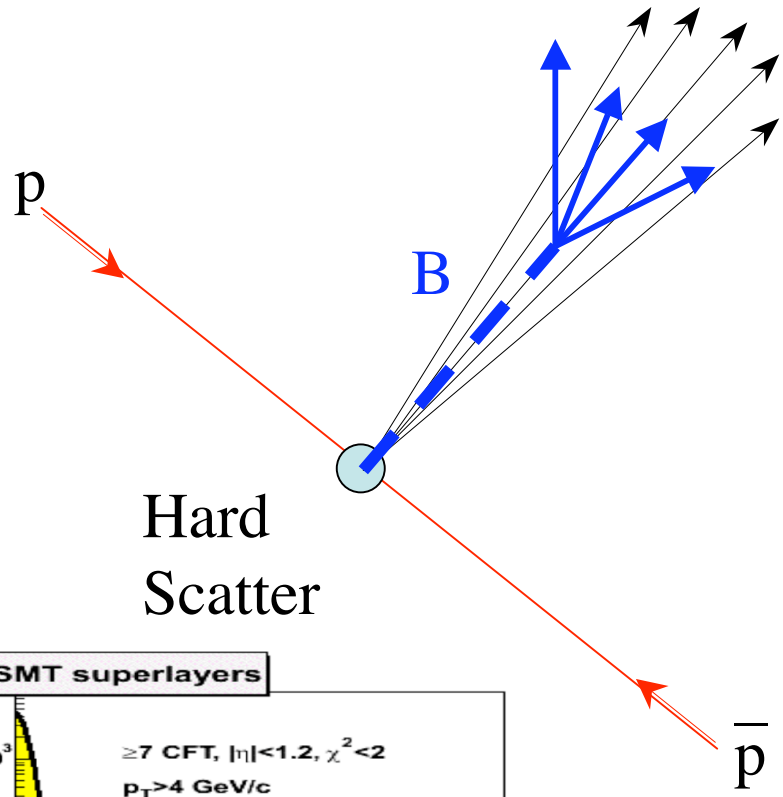
- Exploit b-lifetime
- Counting Signed Impact Parameter (CSIP)
  - S(IP) = IP/σ(IP)
  - IP + if θ > π/2
  - IP - if θ < π/2
- Jet Lifetime IP (JLIP)
- Secondary Vertex (SVT)

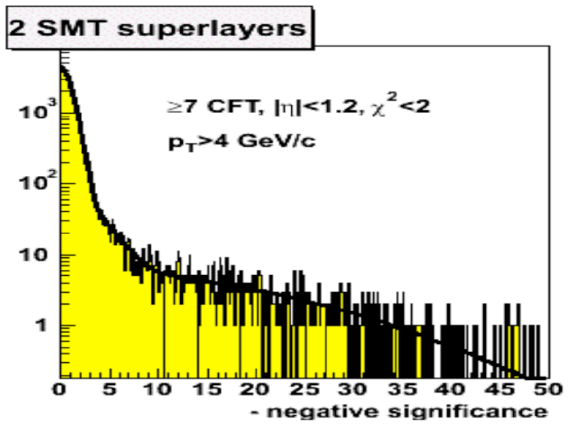




b-tagging Algorithms

- Exploit b-lifetime
- Counting Signed Impact Parameter (CSIP)
- Jet Lifetime IP (JLIP)
  - Measure Resolution Function on Neg SIP
  - Determine Probability per track to be from Primary Vertex
  - Combine all tracks in jet
- Secondary Vertex (SVT)





L0 Impact Parameter Improvement