



Higgs Results



Andy Haas
Columbia University
on behalf of the DØ experiment

CERN Seminar
Sept. 8, 2008

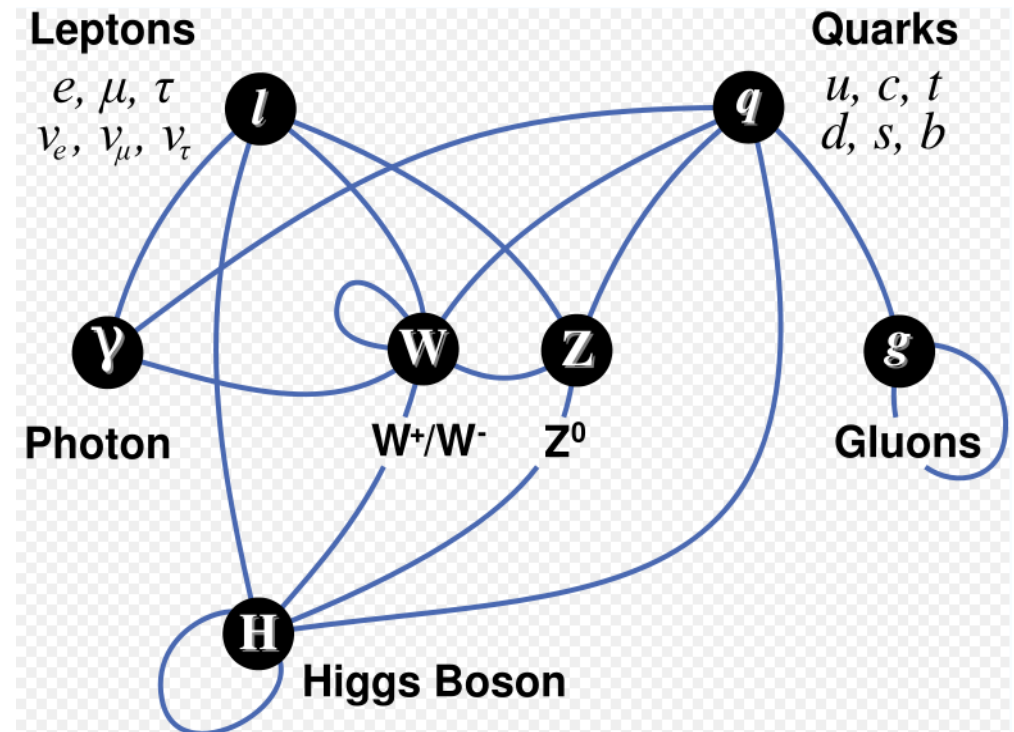
The Higgs Boson

Postulated in the 1960's as a way to give mass to the W/Z bosons

Can also give masses to fermions

Only Standard Model particle not yet observed!

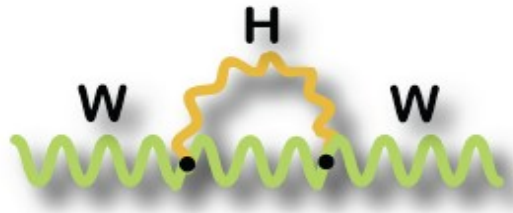
- What is its mass?
 - What are its couplings?
 - Is it a fundamental particle?
 - Is there just one Higgs boson?
-
- Why is $m_h \ll m_{pl}$?
(hierarchy problem)



A critical piece of physics we know very little about!

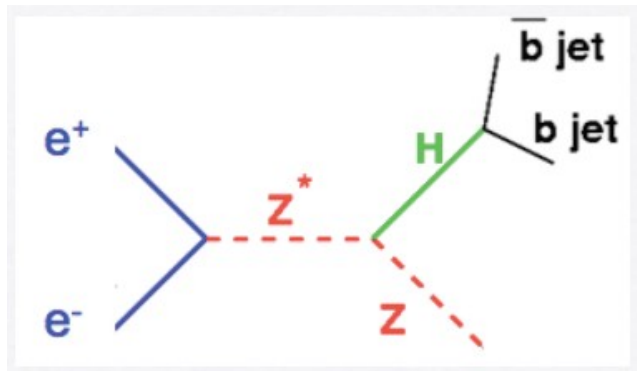
Where's the Higgs?

EW variables sensitive to m_H via radiative corrections:

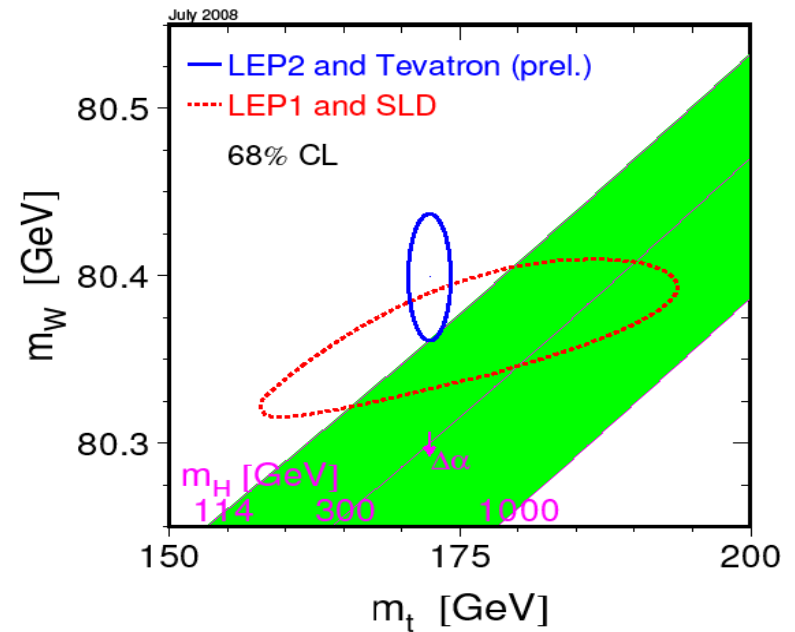
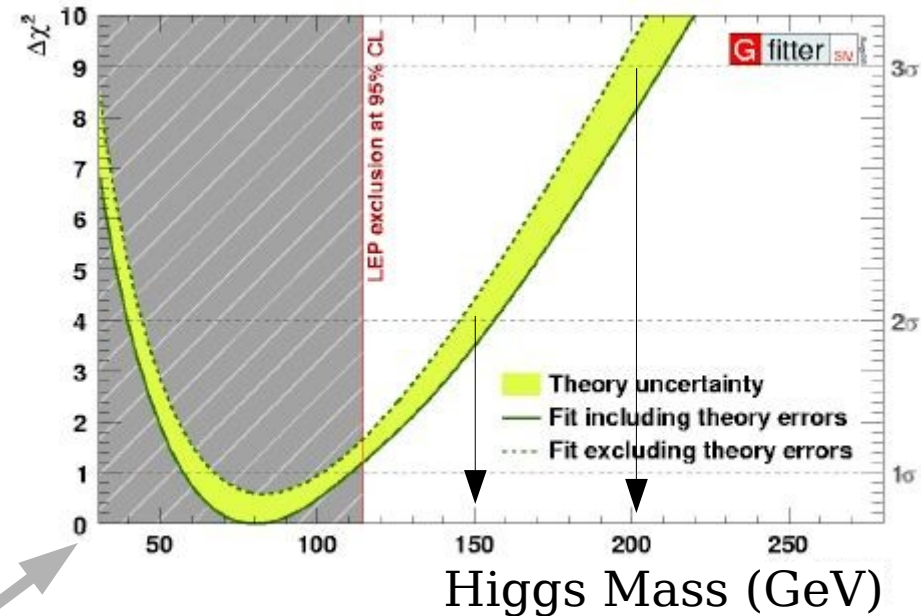


$$\sim \log \frac{m_H}{m_W}$$

LEP II direct: $m_H > 114.4$ GeV



Main LEP channel
(tau also)



DØ and the Tevatron

Running (again) since ~2003

p-pbar, center of mass energy = 1.96 TeV

Data recorded May 31 shown at ICHEP July 31!

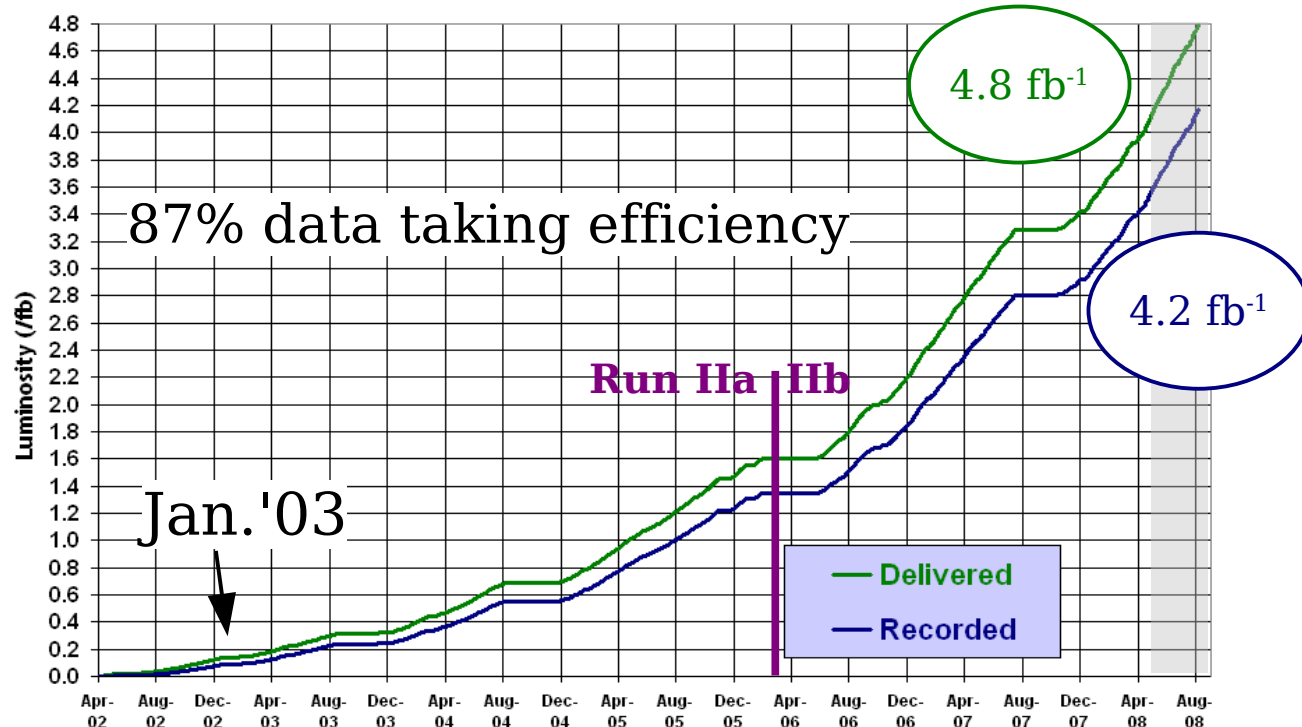
Up to 3.0/fb of good data analyzed so far

~14% data quality loss, ~75% overall efficiency



Run II Integrated Luminosity

19 April 2002 - 24 August 2008

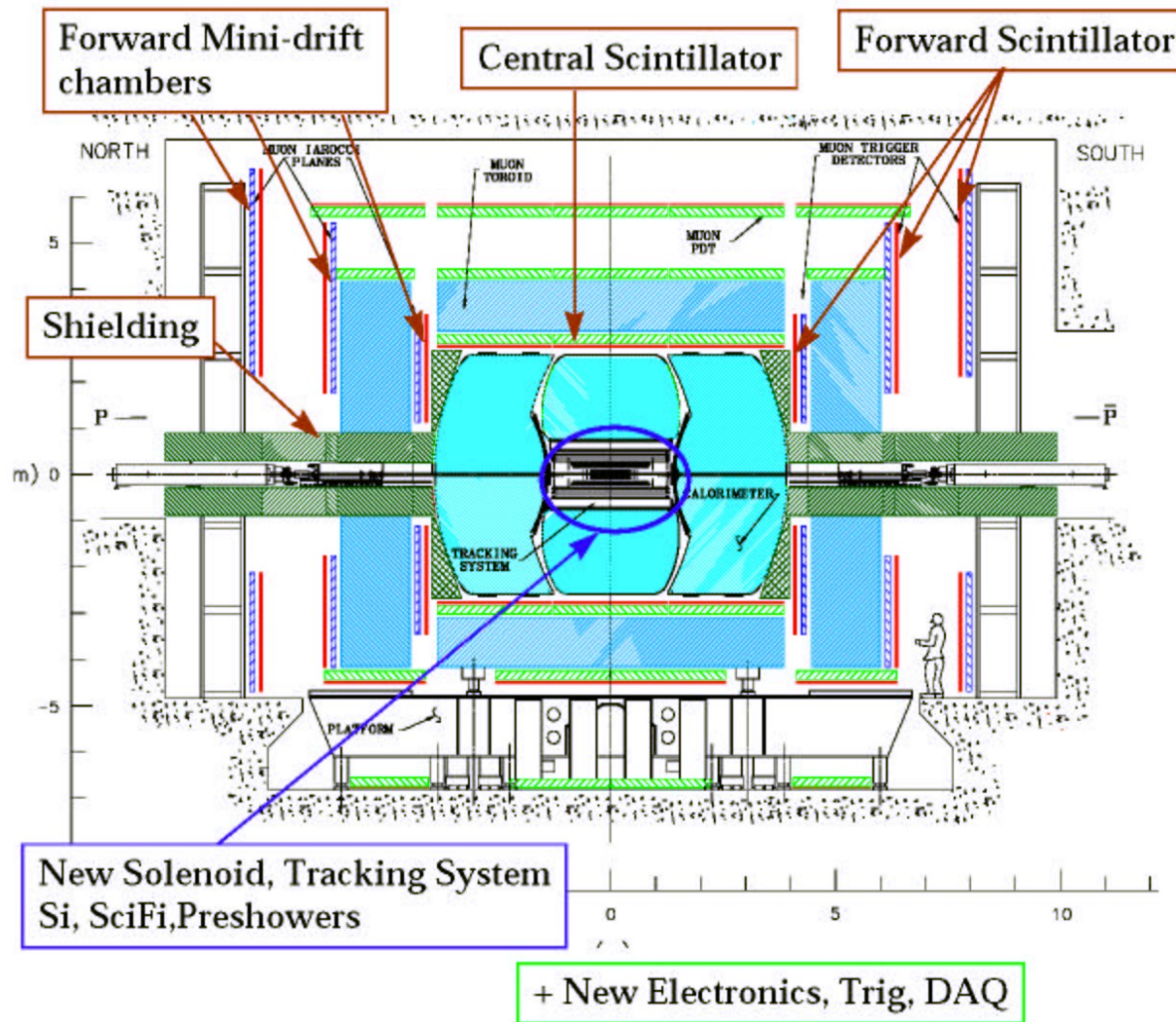


**Tevatron and DØ
both performing
very well!**

Peak luminosity
 $> 3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$



DØ

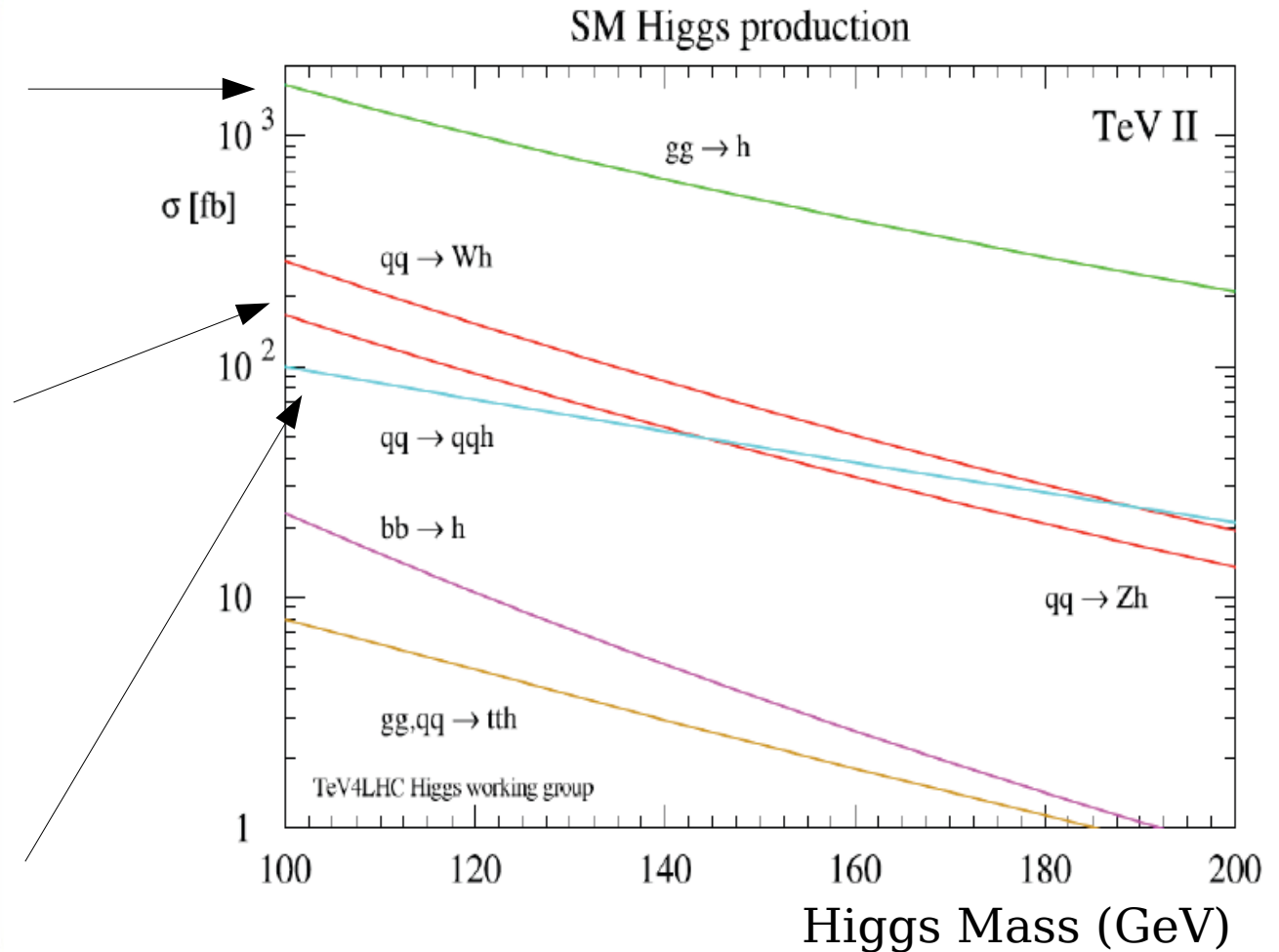
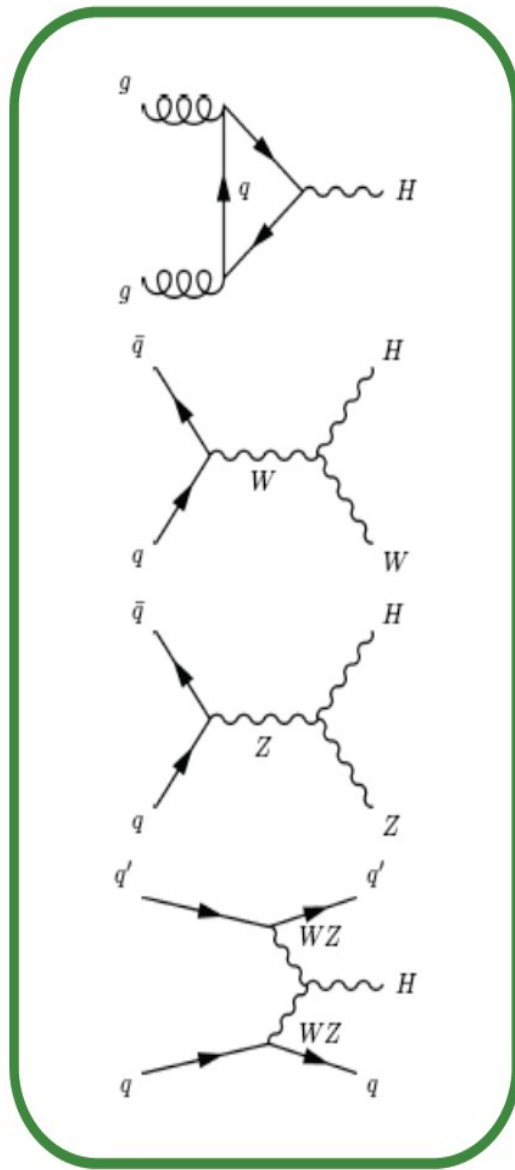


Electrons / photons
Muons
Jets / b-jets / taus
 ME_T



Collaboration of ~550 physicists

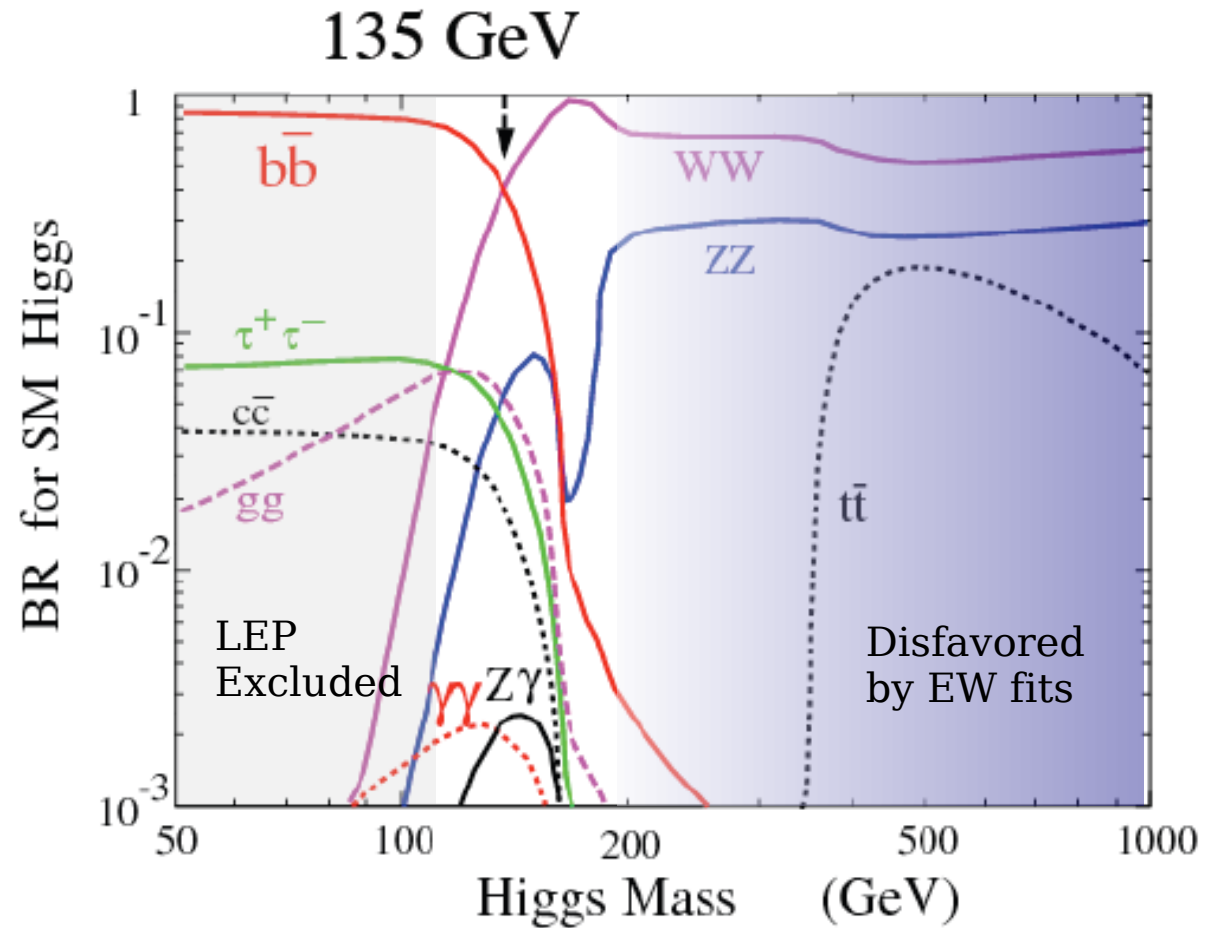
SM Higgs Production at the Tevatron



SM Higgs Decay

Low mass: $h \rightarrow b\bar{b}$

High mass: $h \rightarrow WW$



Main SM Higgs Search Channels

$H \rightarrow bb$
(low mass)

$H \rightarrow WW$
(high mass)

$p\bar{p} \rightarrow H$

~~$H \rightarrow bb$~~

$H \rightarrow WW \rightarrow$
 $lv\ lv$

$p\bar{p} \rightarrow WH$

$WH \rightarrow Wbb \rightarrow$
 $lv\ bb$

$W/Z+H \rightarrow W/Z+WW \rightarrow$
 $l^+l^- l^+ / l^+l^+jj + \nu's$

$p\bar{p} \rightarrow ZH$

$ZH \rightarrow Zbb \rightarrow$
 $ll\ bb$
 $\nu\nu\ bb$

b-jet Tagging

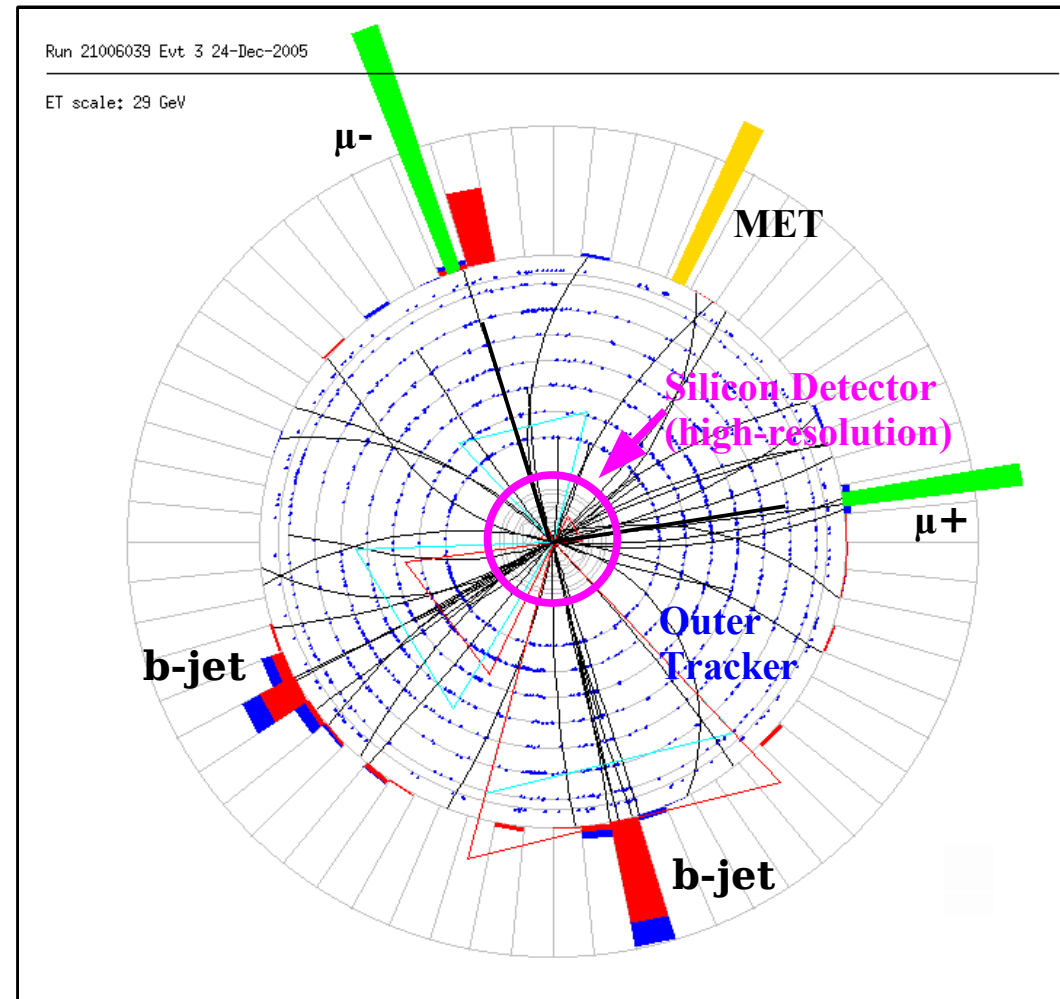
Low mass: **$h \rightarrow b\bar{b}$**

Identify jets with b's !

- Reduce backgrounds by factor of ~ 50 (with one “loose” b-tag)

B hadrons are “long”-lived

- $\gamma_{ct} = \sim 3\text{mm}$
- Reconstruct tracks *with high-resolution silicon*



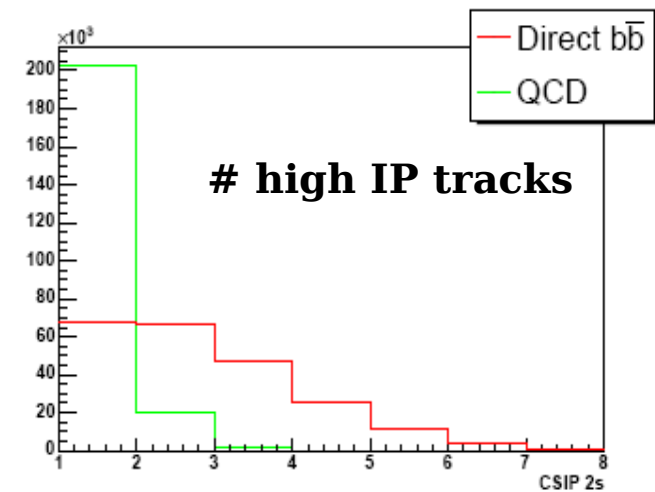
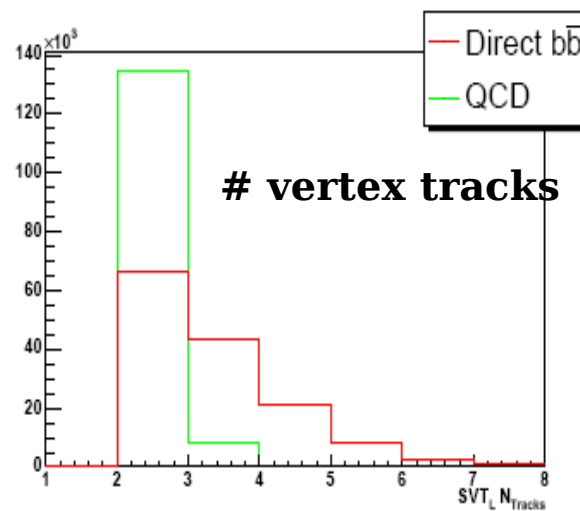
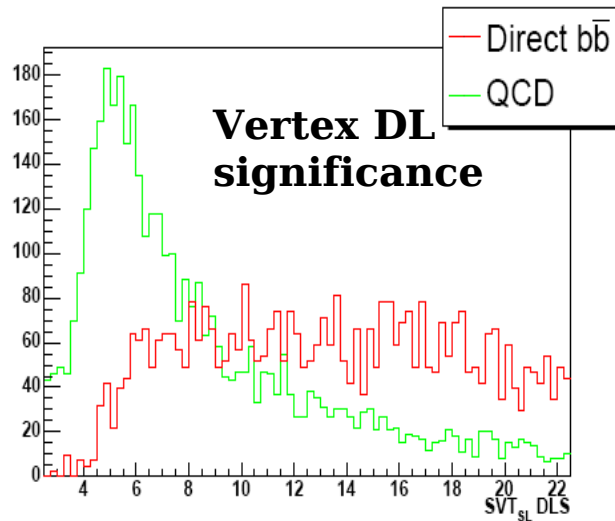
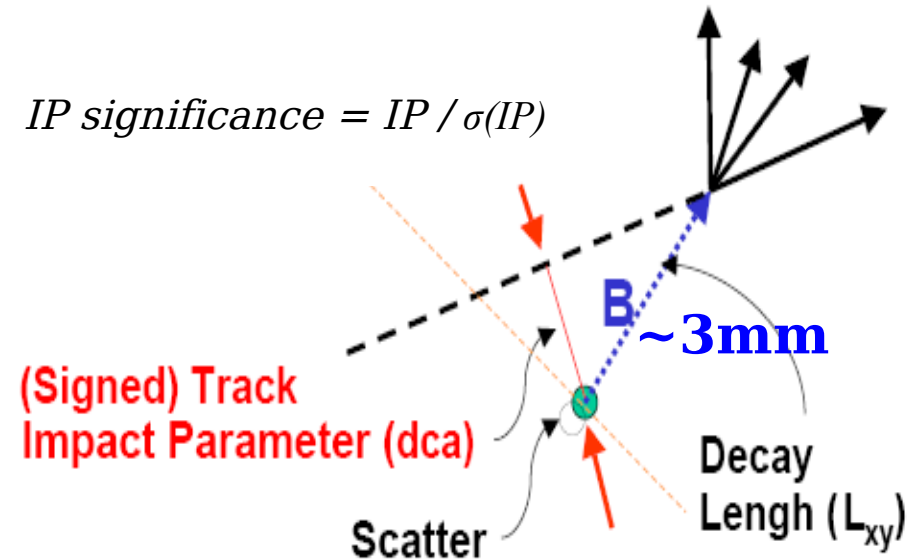
Simulated $ZH \rightarrow \mu\mu b\bar{b}$ event

b-jet Tagging

Many variables with separation:

- Vertex: *Decay Length Signif.*, *#tracks*, *#vertices*, *mass*, χ^2
- *#high IP sig. tracks*, combined light-jet prob.

$$IP\ significance = IP / \sigma(IP)$$



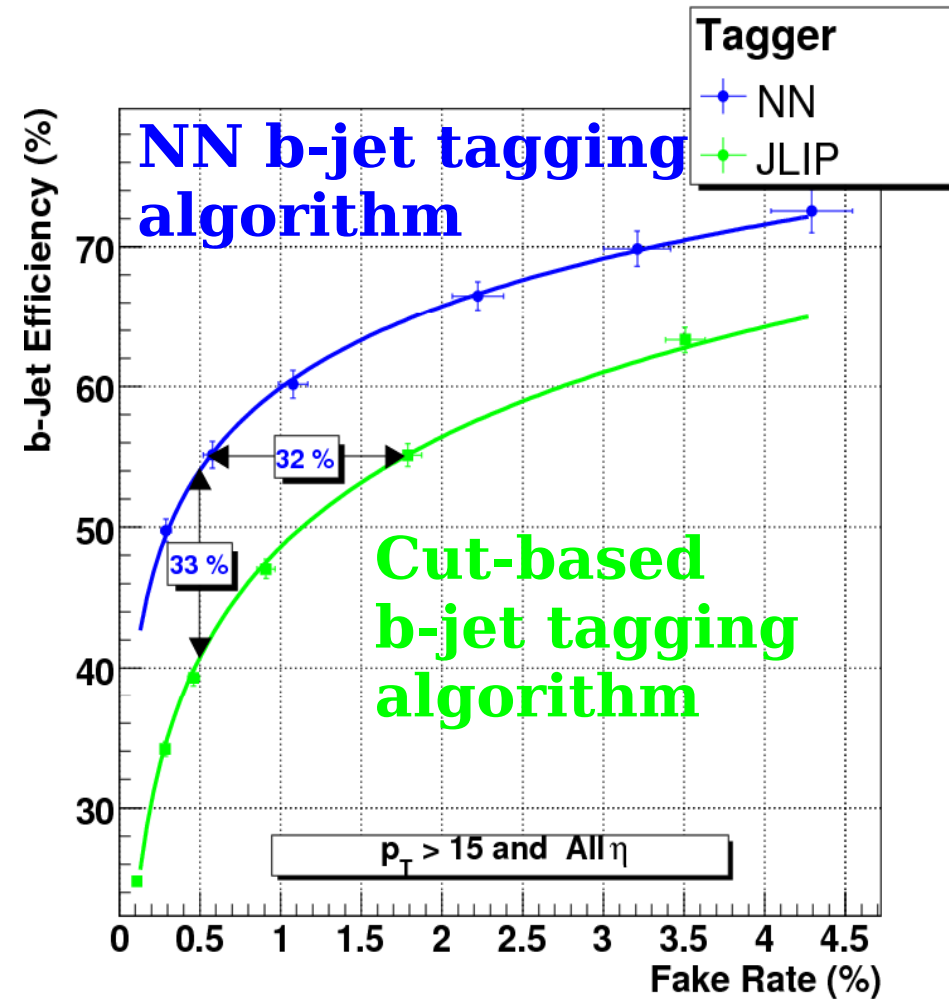
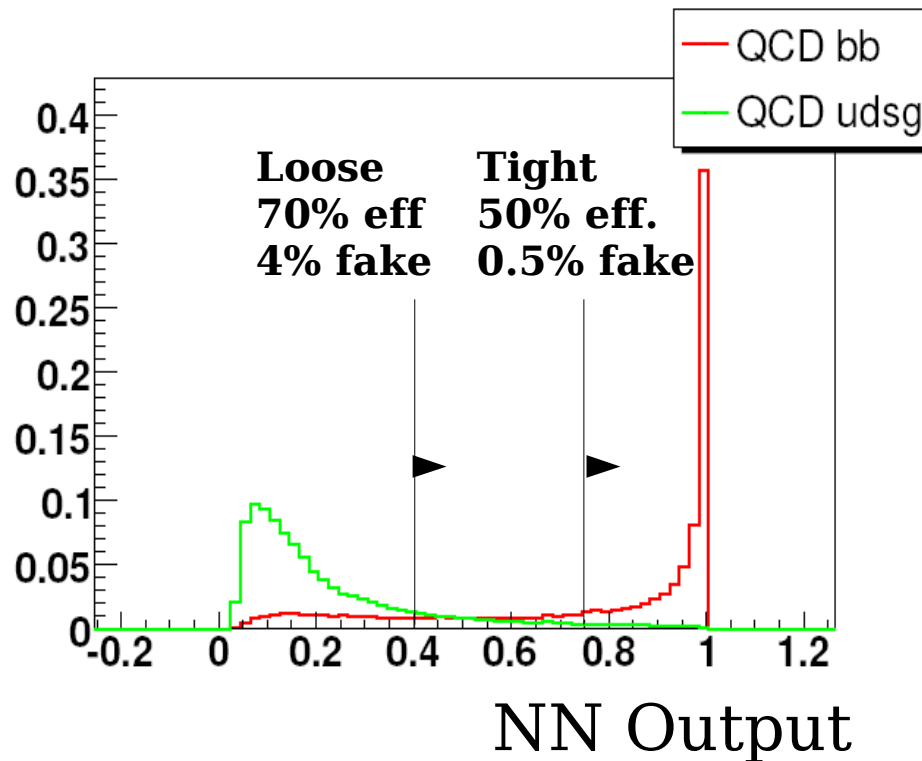
...

b-jet Tagging

Train artificial Neural Network on simulated events

- optimized inputs, training method, network topology

Test NN efficiency and fake rate using *real data*



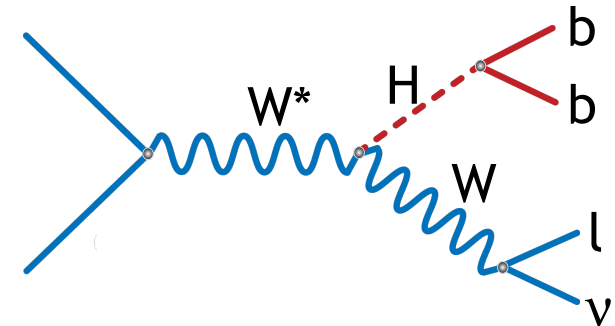
Equivalent to 2.5x as much data for a double-b-tag analysis!

$$WH \rightarrow (e/\mu)\nu bb$$

Select lepton (e, μ) + ME_T events -- lepton and lepton+jets triggers

QCD: jets which fake leptons

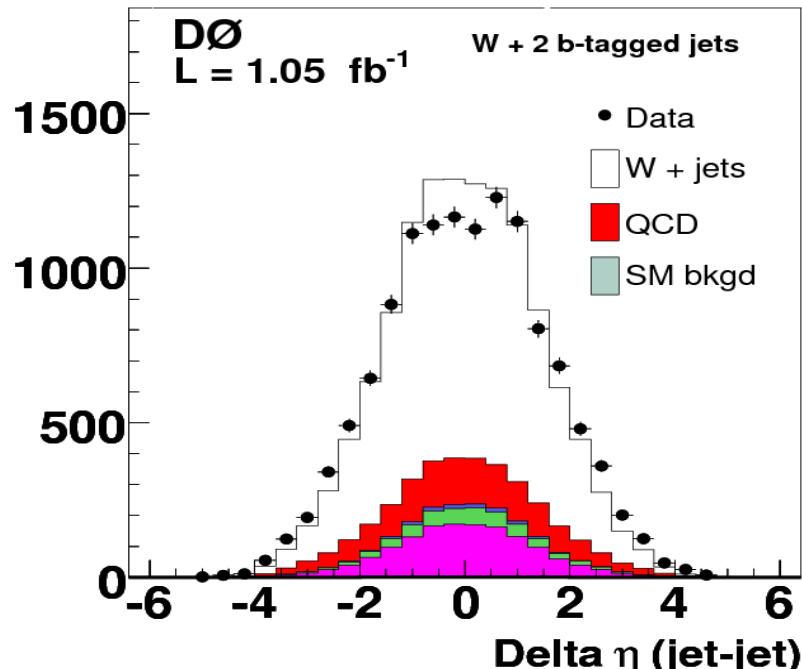
- Measured from data in low ME_T events



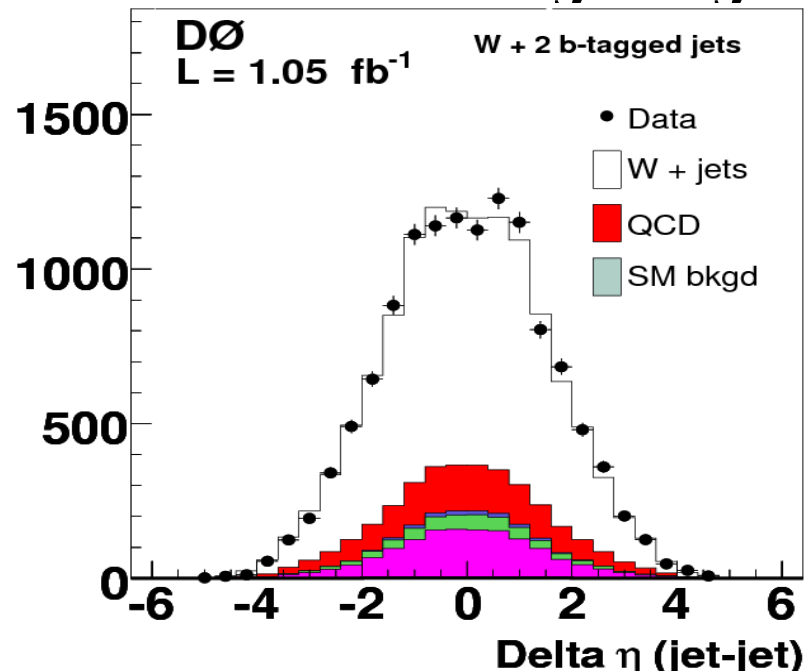
ALPGEN MC used to model W+jets

- Re-weight angular variables to data (before b-tagging)

Before re-weighting



After re-weighting



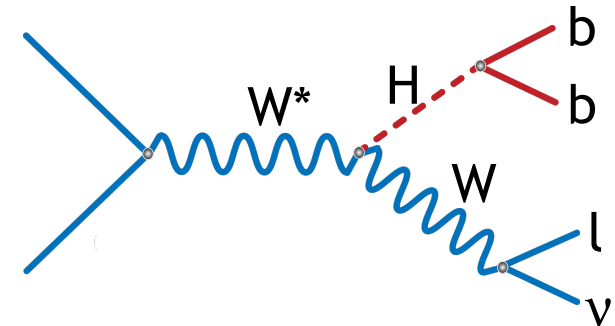
Also $\Delta\phi$

$$WH \rightarrow (e/\mu)\nu bb$$

Select lepton (e, μ) + ME_T events -- lepton and lepton+jets triggers

QCD: jets which fake leptons

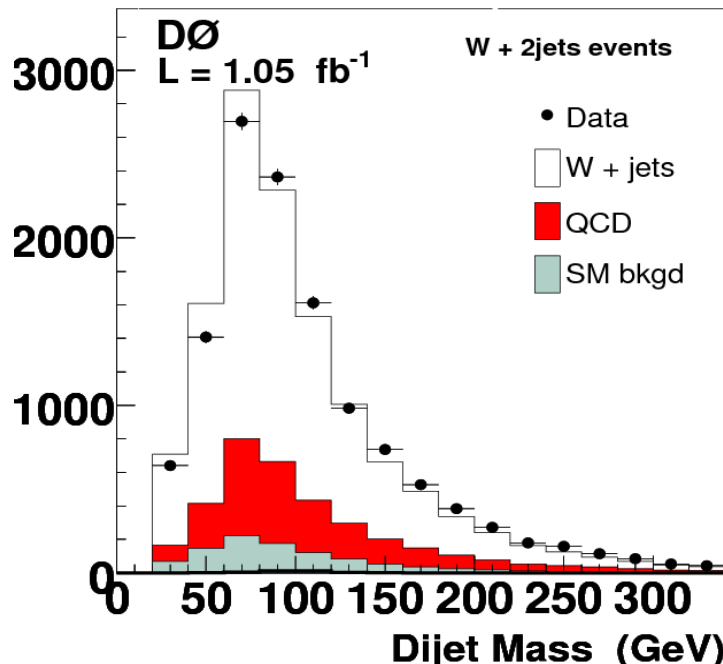
- Measured from data in low ME_T events



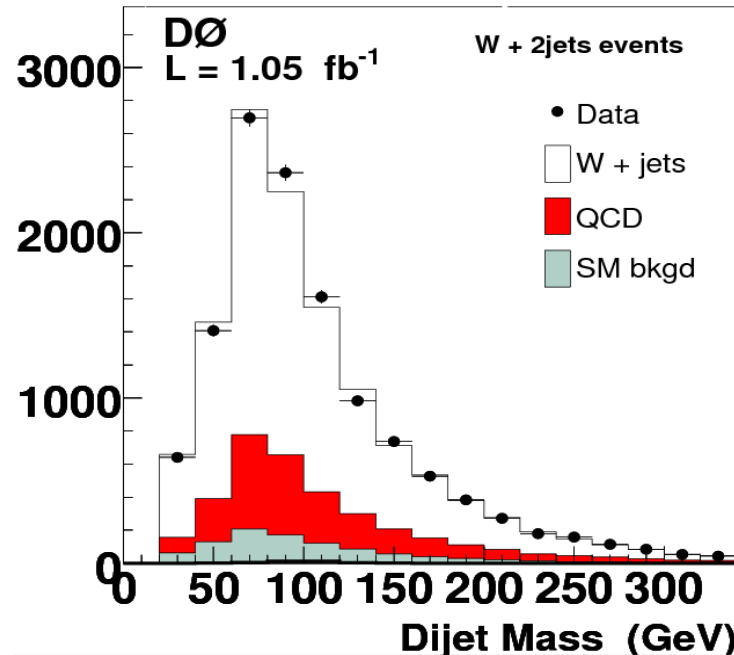
ALPGEN MC used to model W+jets

- Re-weight angular variables to data (before b-tagging)

Before re-weighting



After re-weighting



Improved
dijet mass
modeling

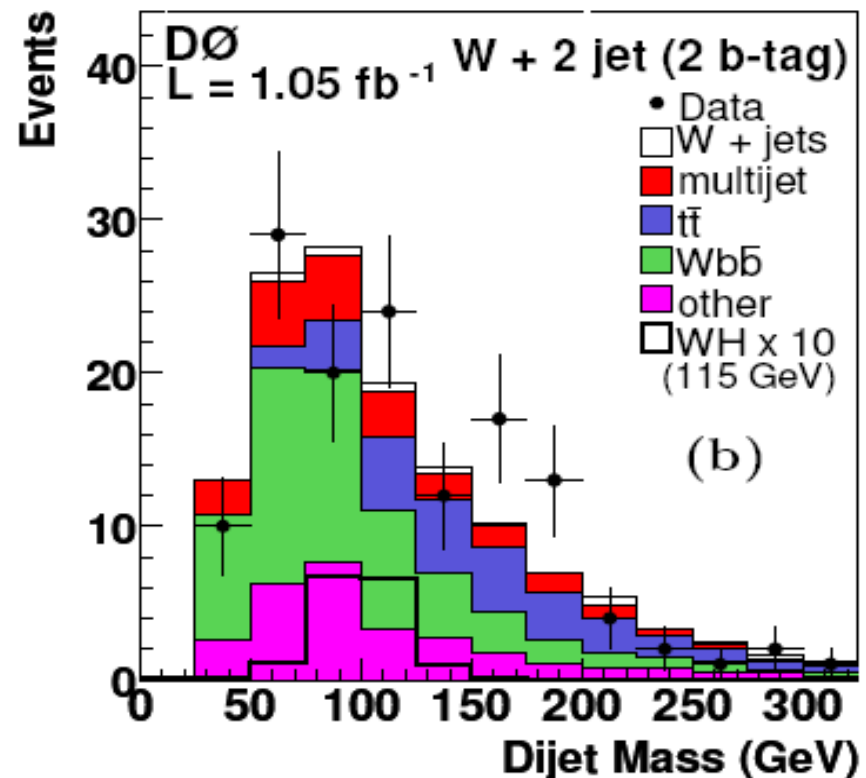
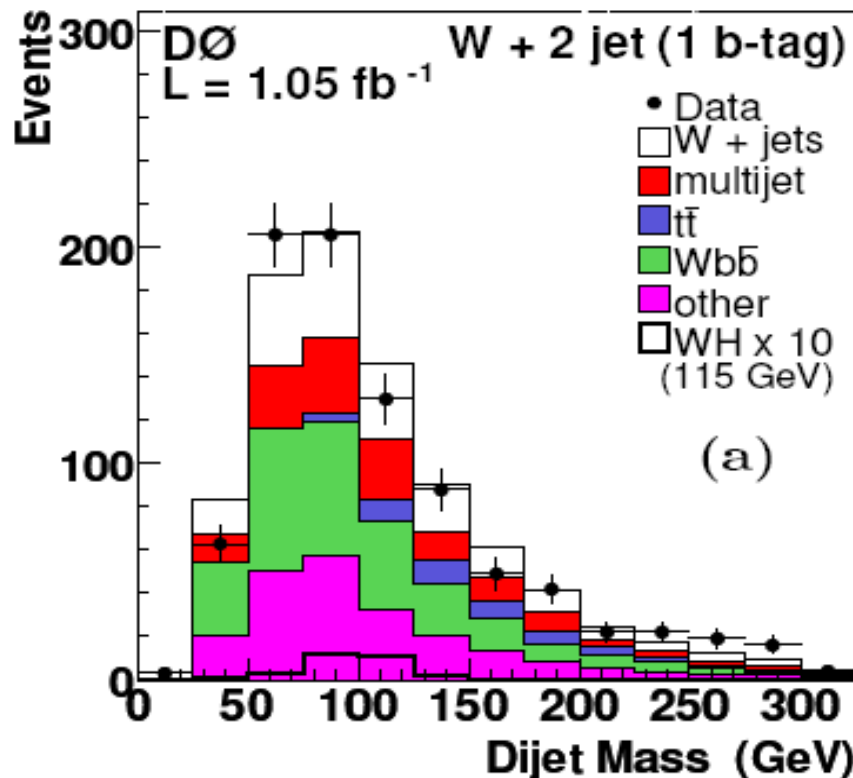
$WH \rightarrow (e/\mu)\nu b\bar{b}$

Apply b-tagging to reduce W+light-jet background

Add single-tight b-tagging to add acceptance

Single-tight tag sample
(and not double-loose)

Double-loose tag sample



$$WH \rightarrow (e/\mu)\nu bb$$

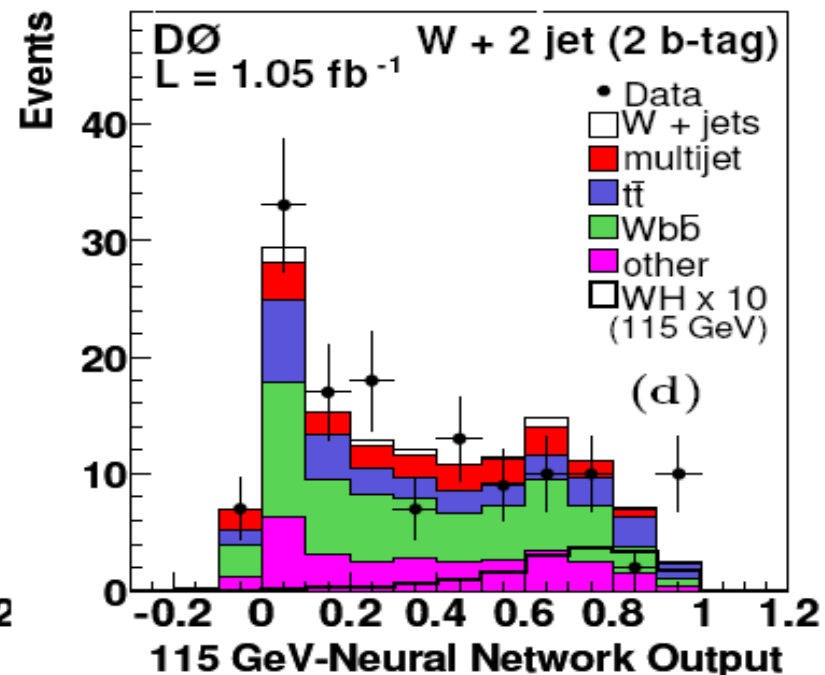
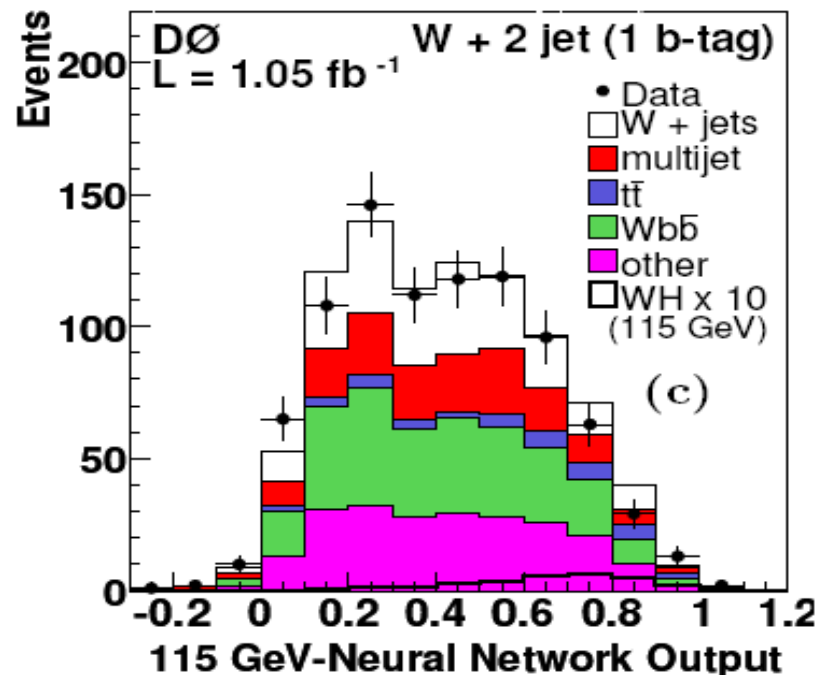
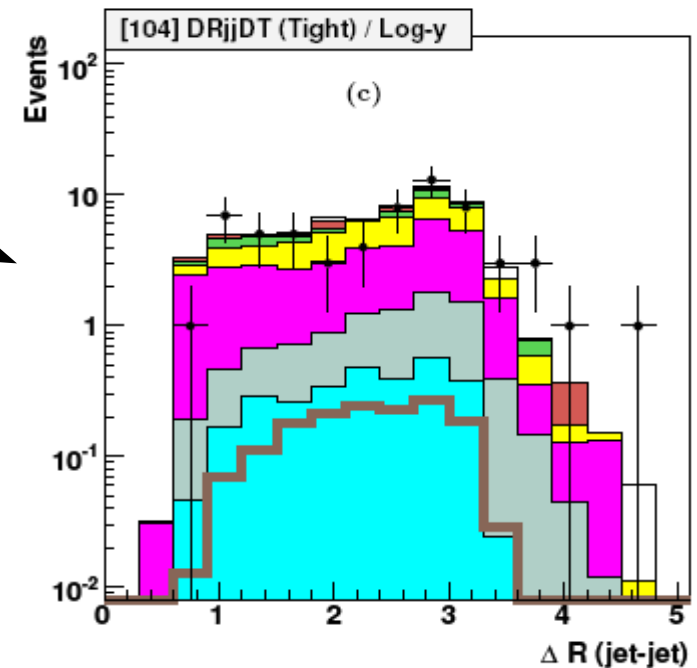
Artificial Neural Network used to increase S/B using more variables

Dijet mass

Angle between jets

Jet, lepton energies

W transverse momentum



$$WH \rightarrow (e/\mu)\nu b\bar{b}$$

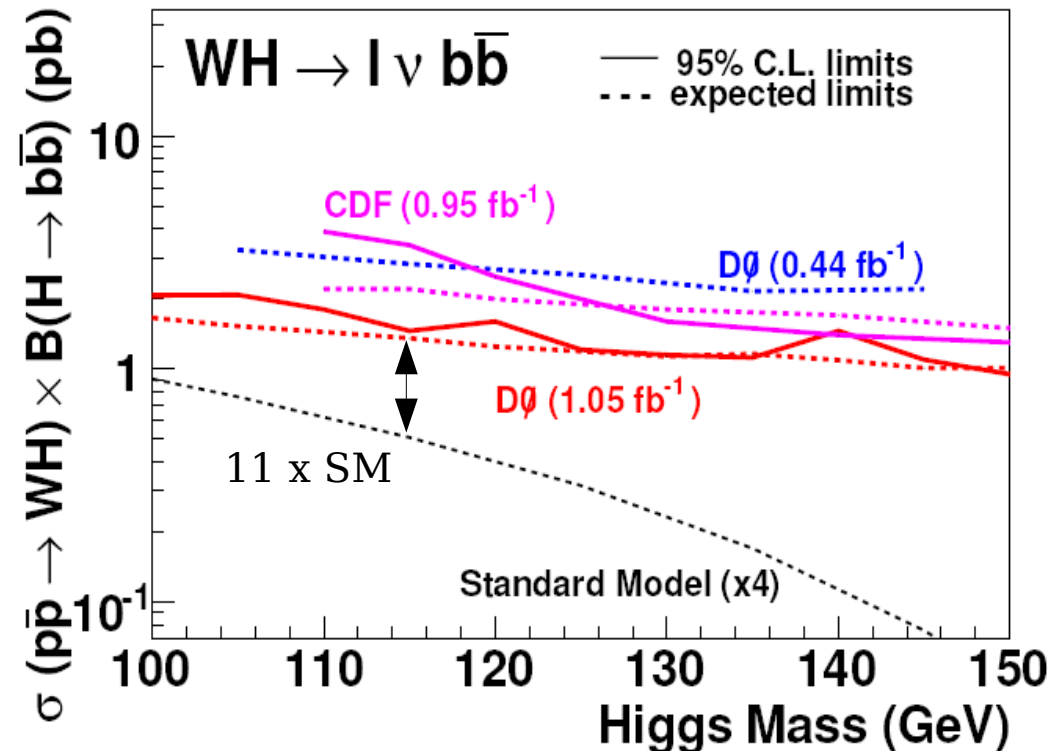
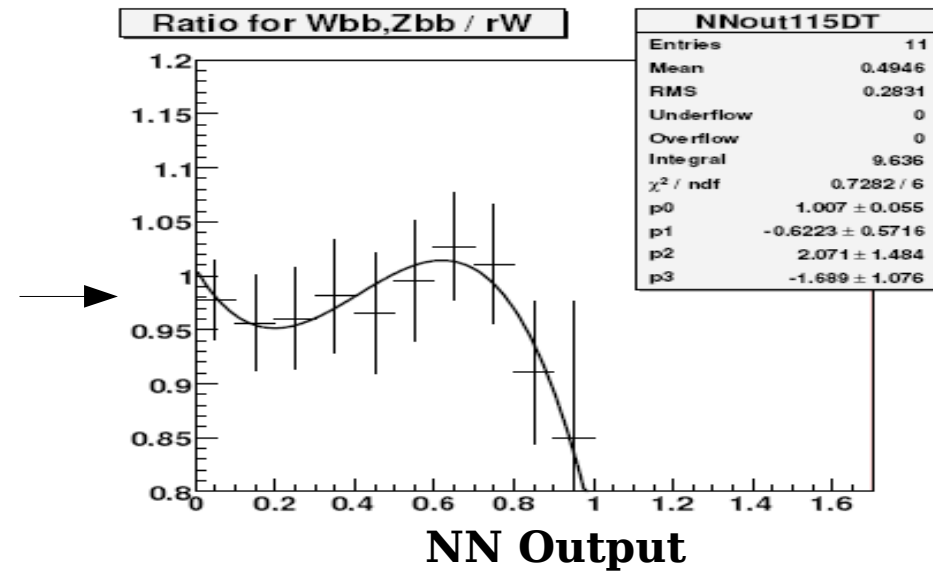
Use NN outputs to set limits
Full treatment of flat and *shape systematics*

Also take advantage of better acceptance
~2x more sensitive than cut-based analysis

Submitted for publication
arXiv:/0808.1970 [hep-ex]

Currently using 1.7/fb
Limit is ~8.5x SM at 115 GeV

Soon extend larger 3/fb data set

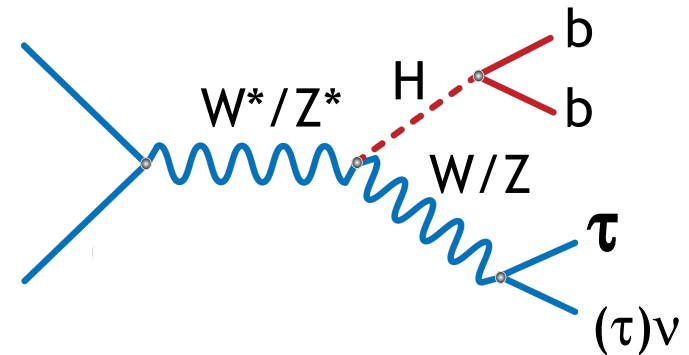


$WH \rightarrow \tau \nu b \bar{b}$

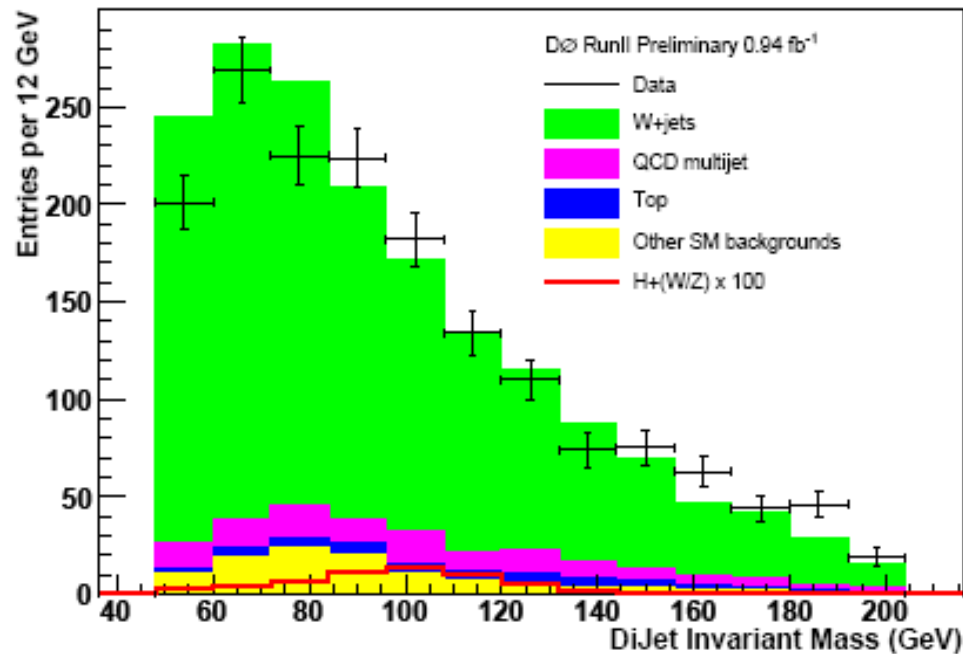
New channel!

1/fb only, trigger on jets + ME_T

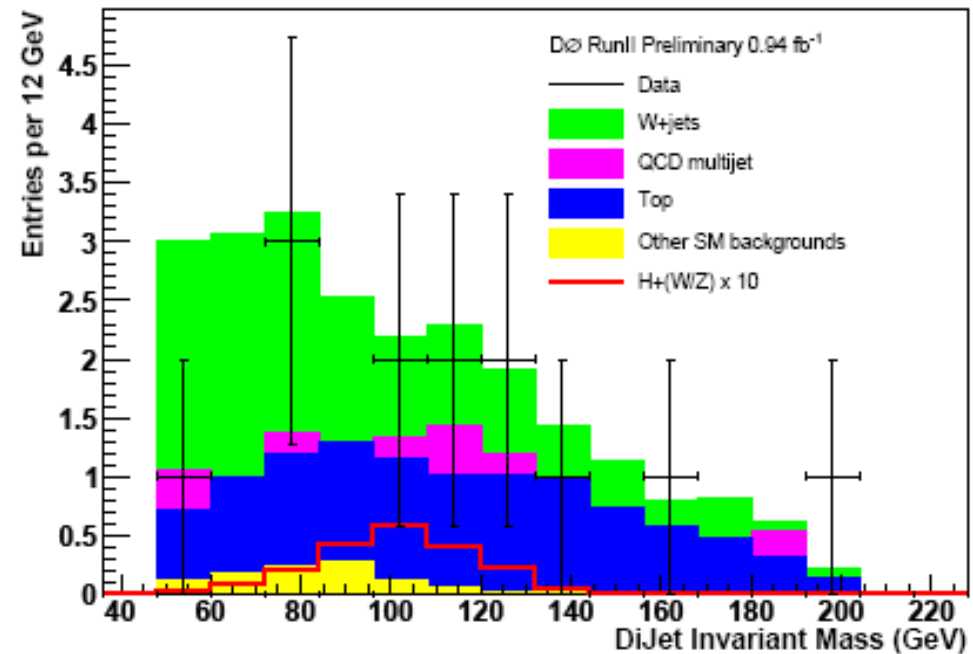
Limit $\sim 35 \times \text{SM} @ 115 \text{ GeV}$



Before b-tagging



After b-tagging



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

Very clean signature!

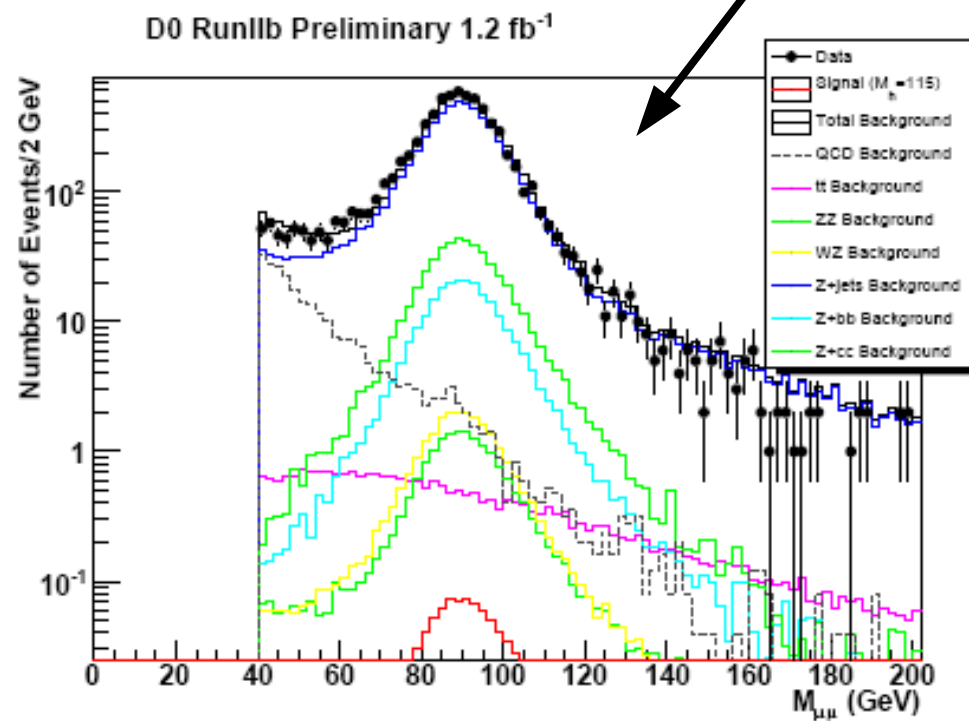
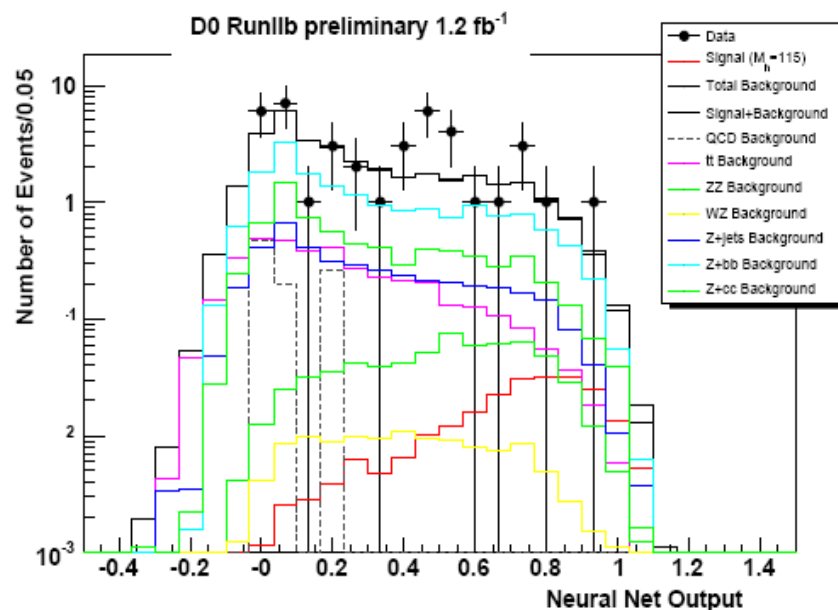
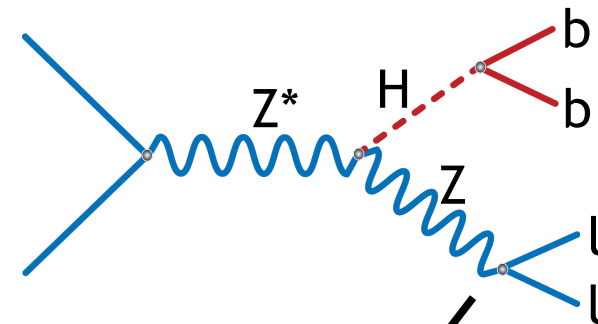
Select di-muon and di-electron events (di-tau underway)

- OR of single and double lepton triggers $\sim 100\%$ efficient

Recently updated analyses to 2.3/fb

Neural Network used (ME underway)

Limit $\sim 12\times$ SM @115 GeV



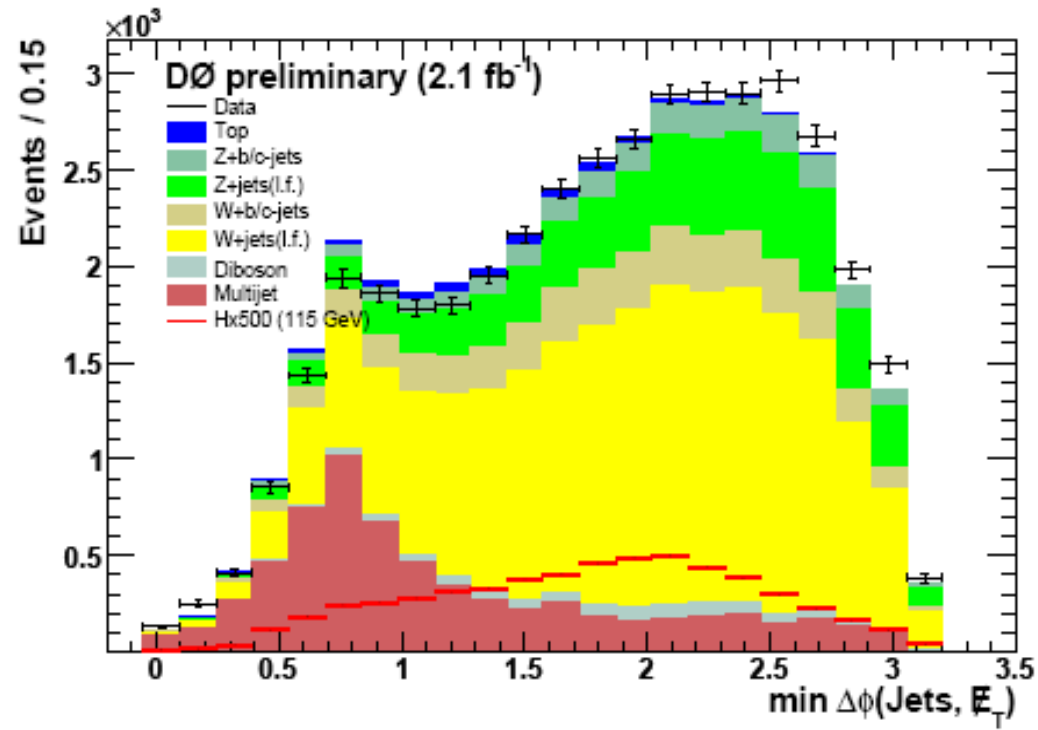
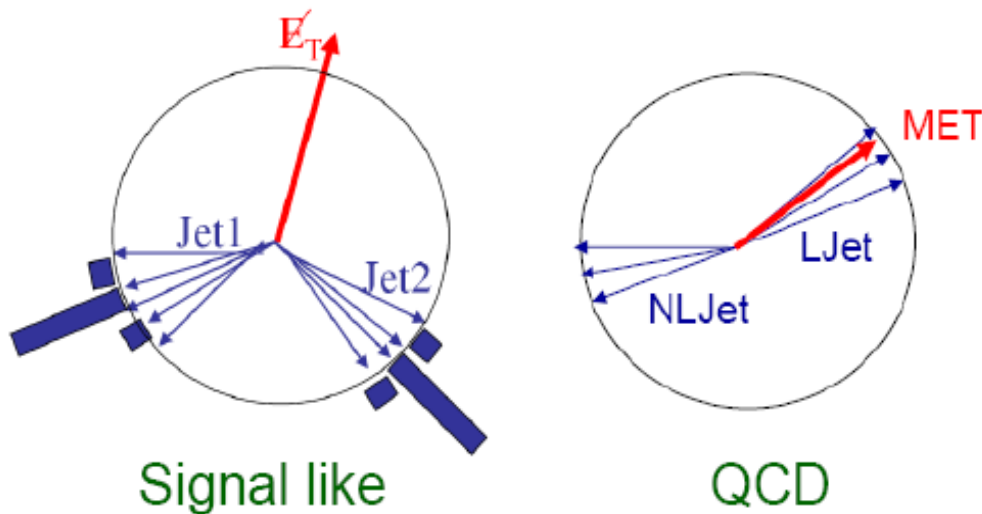
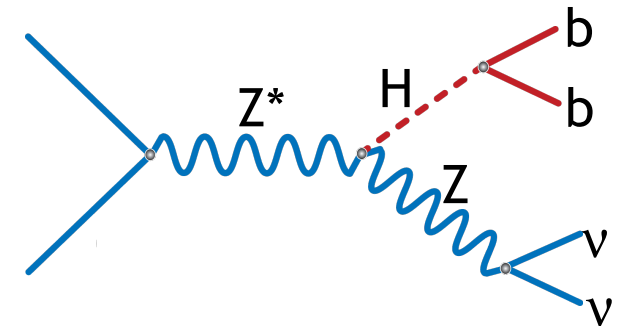
$ZH \rightarrow \nu\nu bb$

2.1/fb analyzed, triggered on jets and ME_T

Also include WH signal when lepton is lost

QCD estimated from data

- Simulation checked in W+jets selection (requiring a lepton)

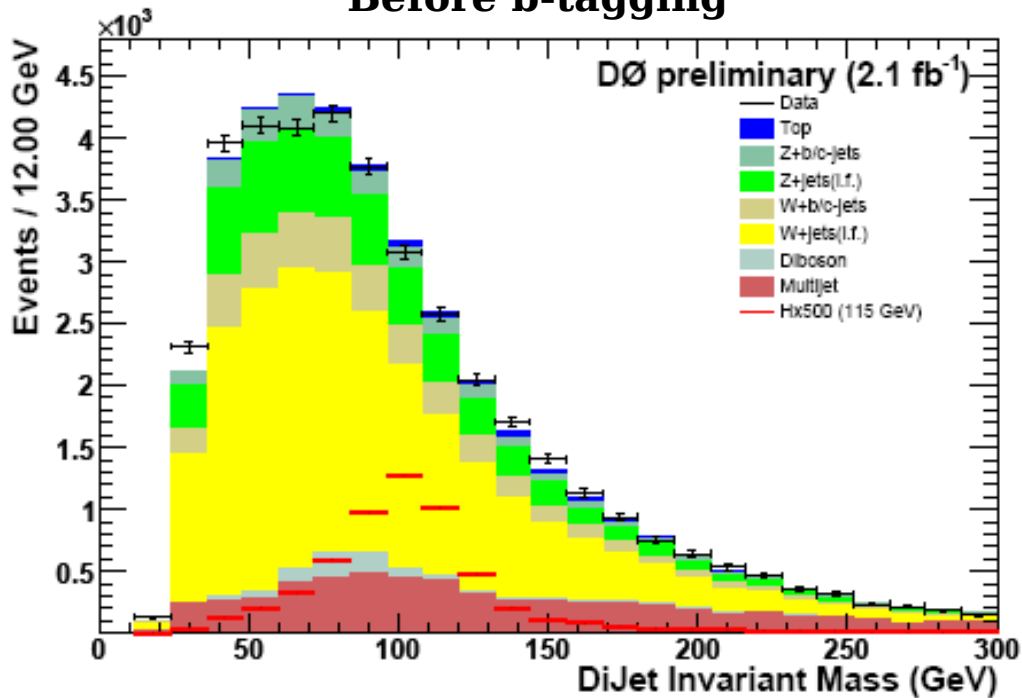


$ZH \rightarrow \nu\nu bb$

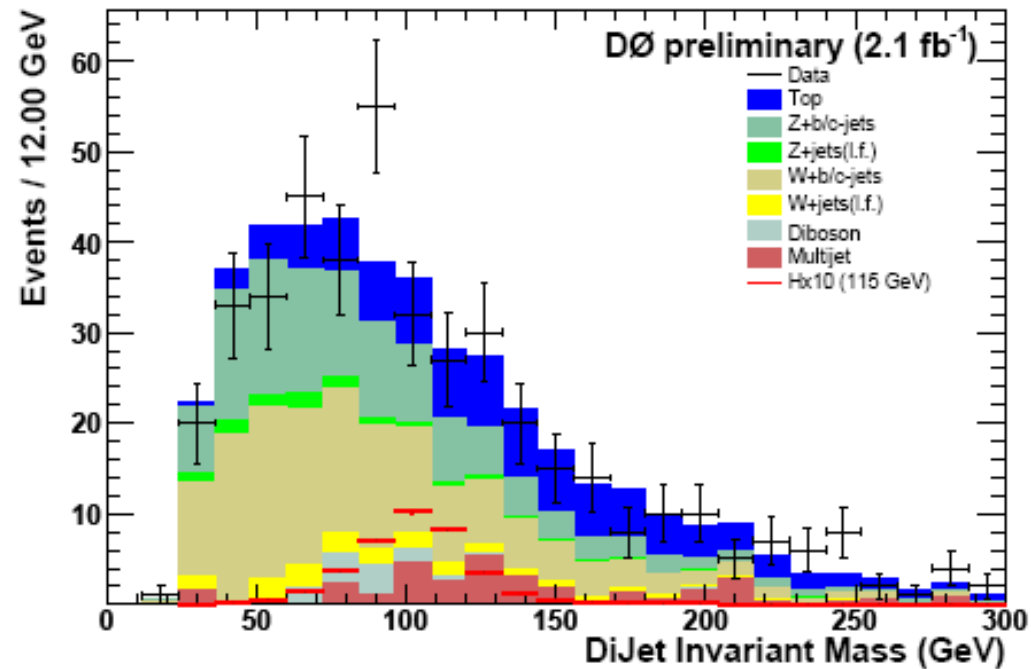
Checks performed before b-tagging

Look for signal after b-tagging

Before b-tagging



After (double) b-tagging



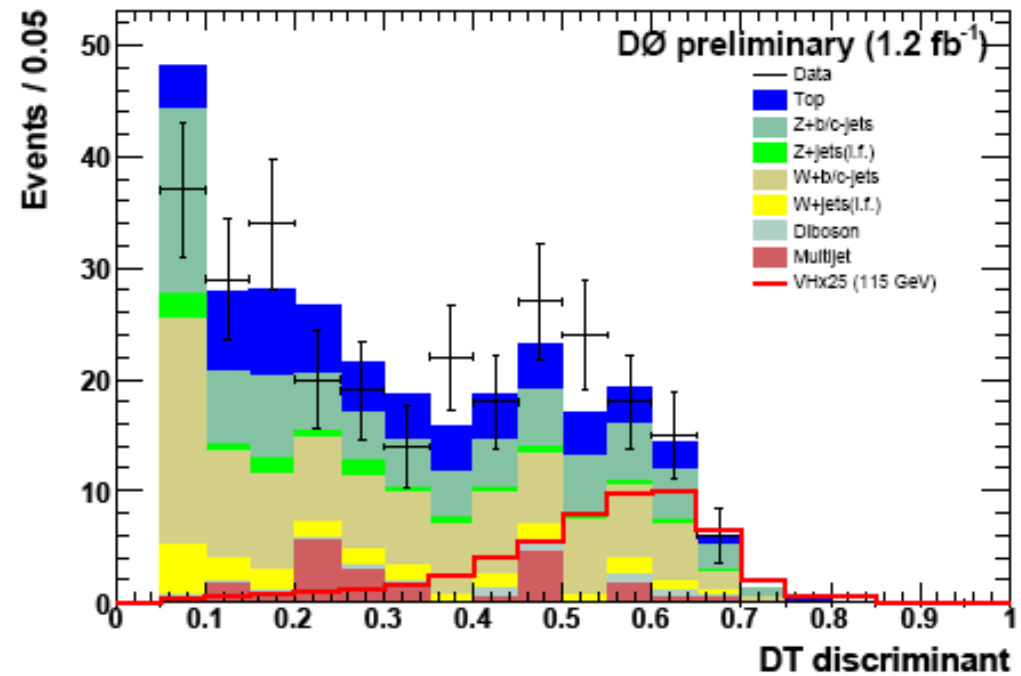
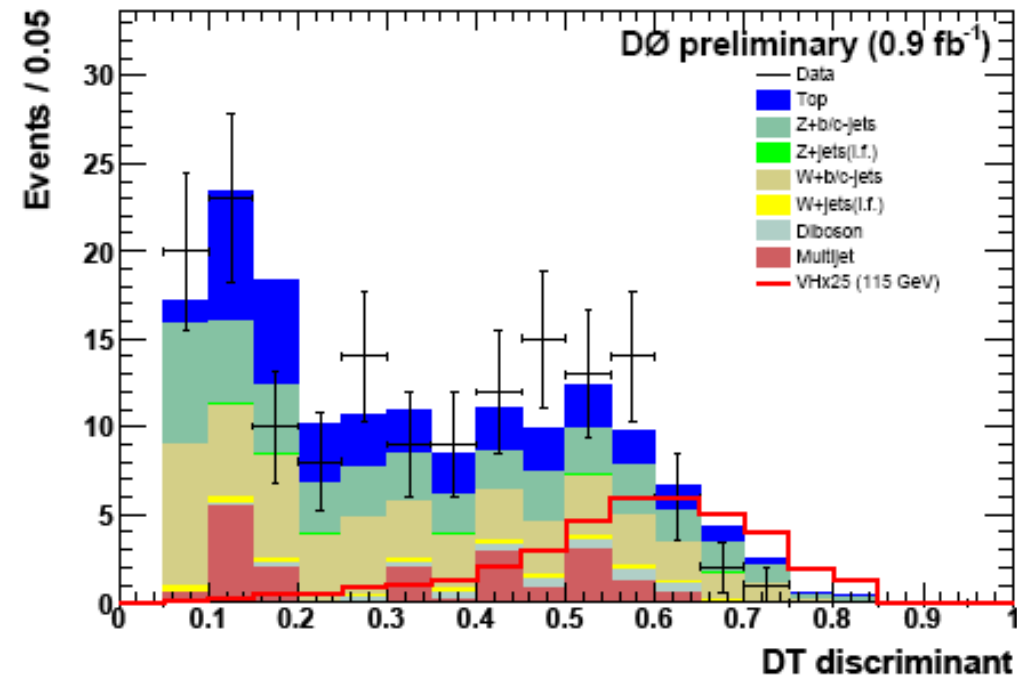
$ZH \rightarrow \nu\nu bb$

Use Boosted Decision Tree to separate signal from background

Limit $\sim 8\times$ SM @115 GeV

Run IIa

Run IIb (analyzed so far)



tth → tt bb

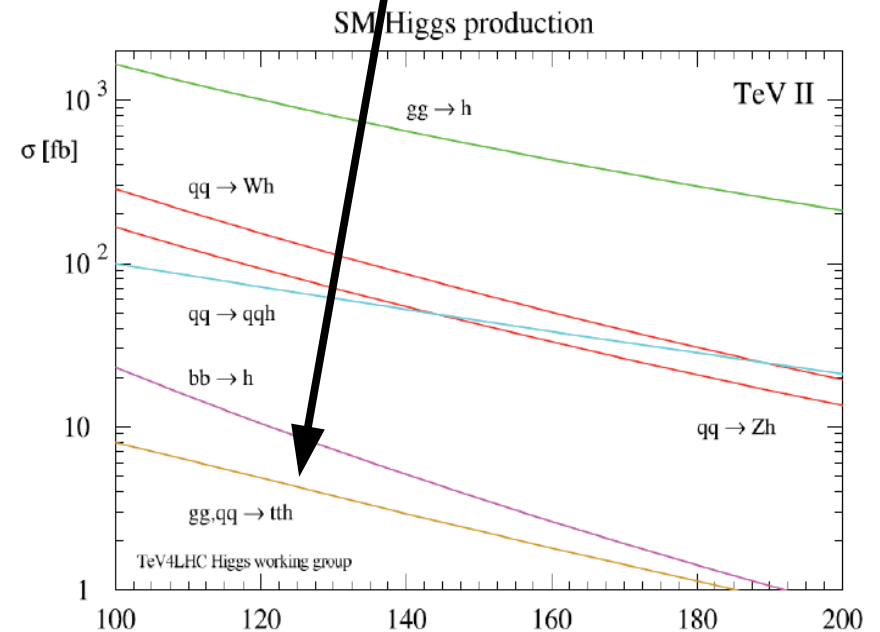
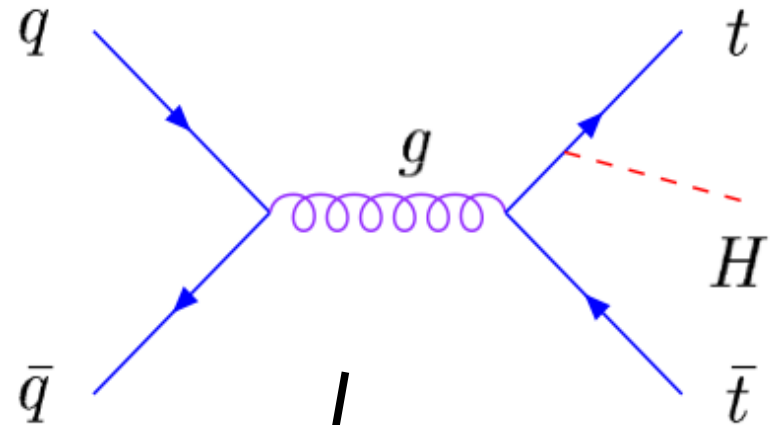
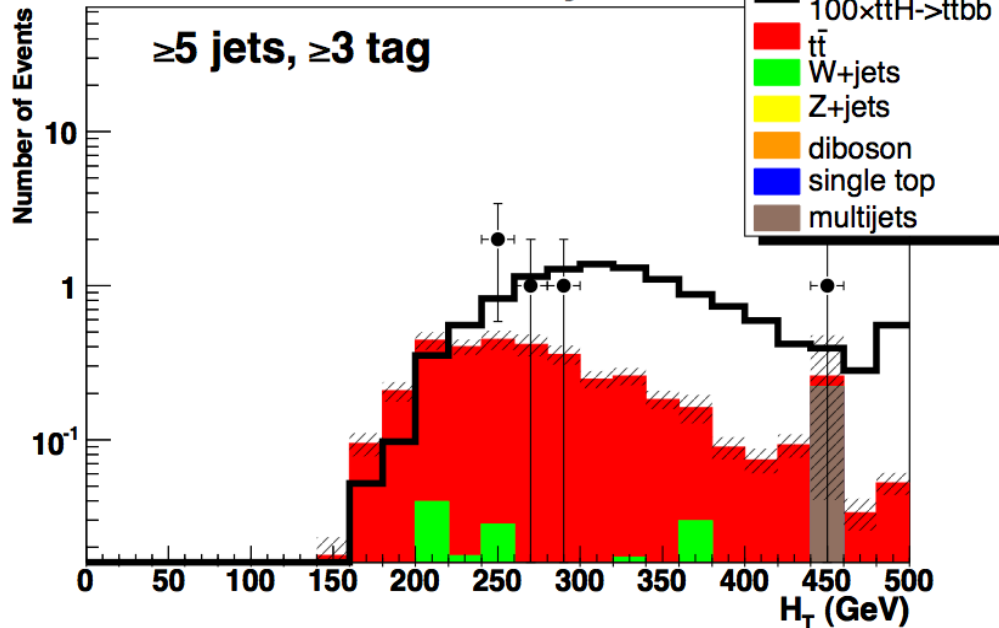
New channel!

Tiny cross-section, but relatively clean

- Lepton + ME_T + jets
- 1,2, or **at least 3** b-tagged jets

Limit $\sim 45\times$ SM @115 GeV

D0 RunII 2.1 fb⁻¹ Preliminary



$$h \rightarrow \gamma\gamma$$

Tiny cross-section, but relatively clean

- Can be enhanced by new physics (fermio-phobic)

Advanced photon-ID Neural Network

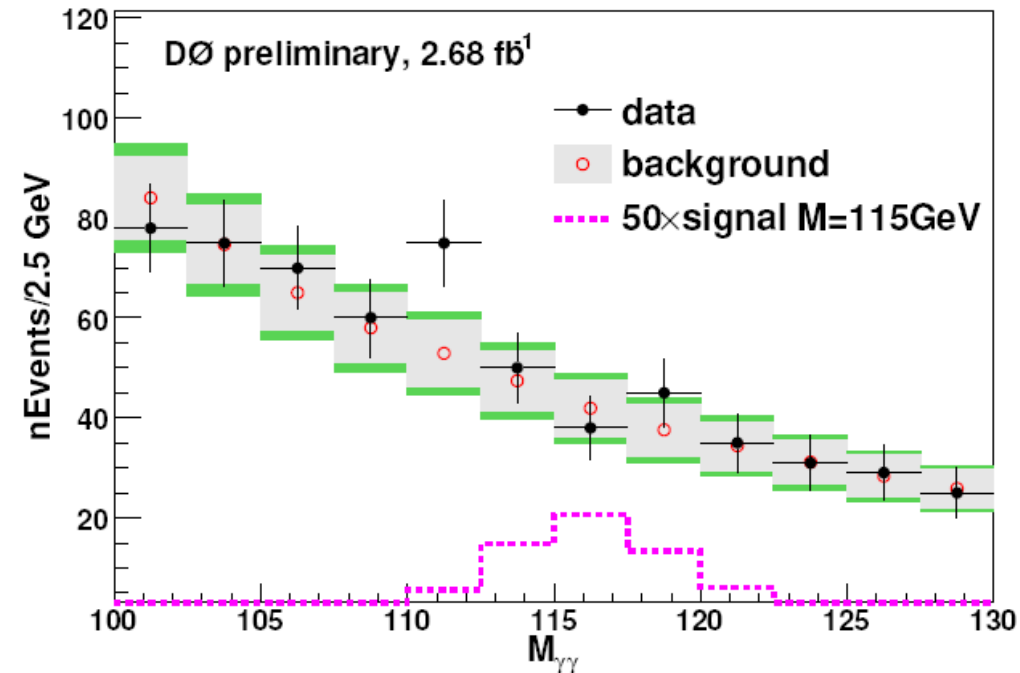
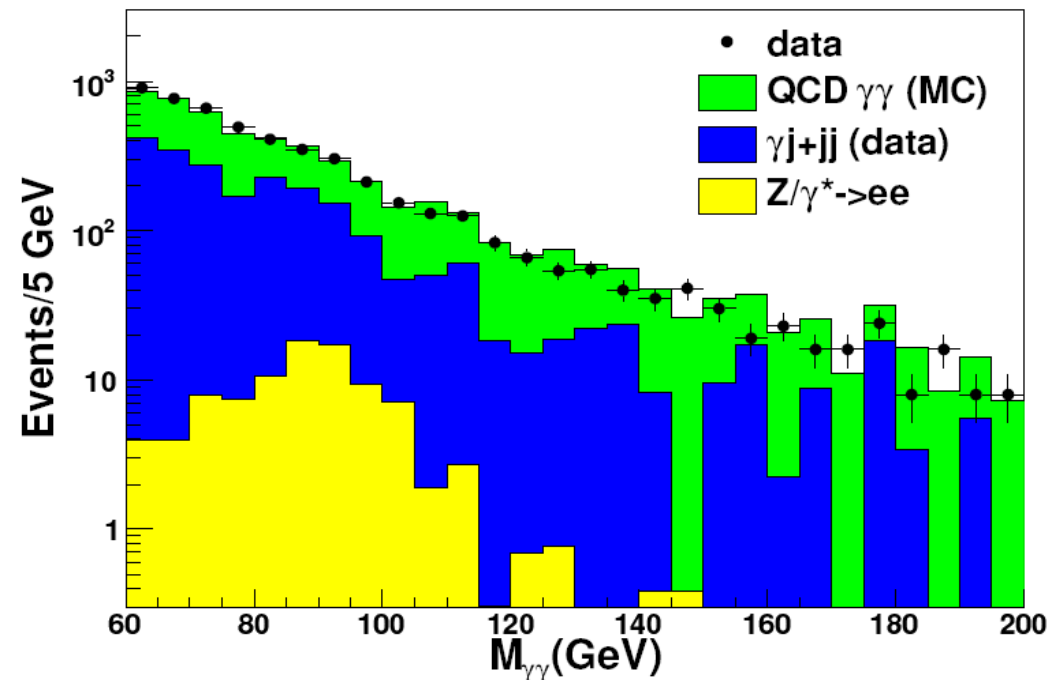
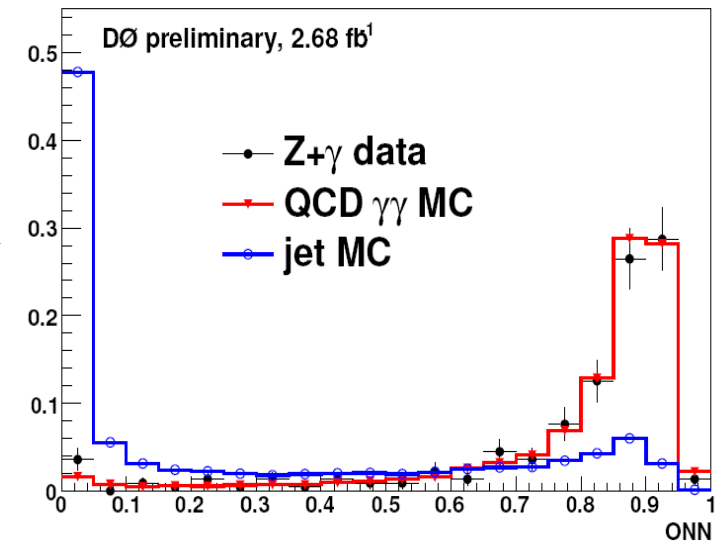


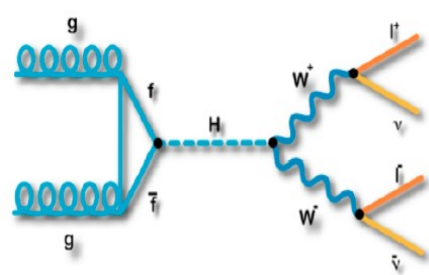
Di-jet and γ +jet measured in data

Data agrees with Pythia re-weighted to DIPHOX

Important channel for LHC, tested at DØ

Limit $\sim 23\times$ SM @115 GeV





$$H \rightarrow WW \rightarrow l\nu l\nu$$

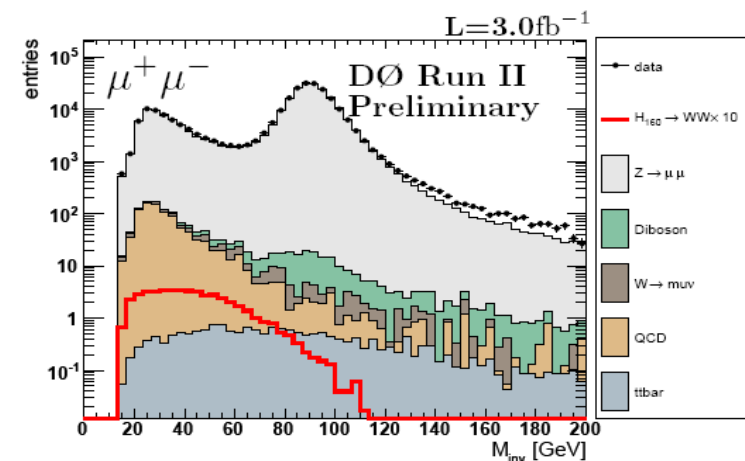
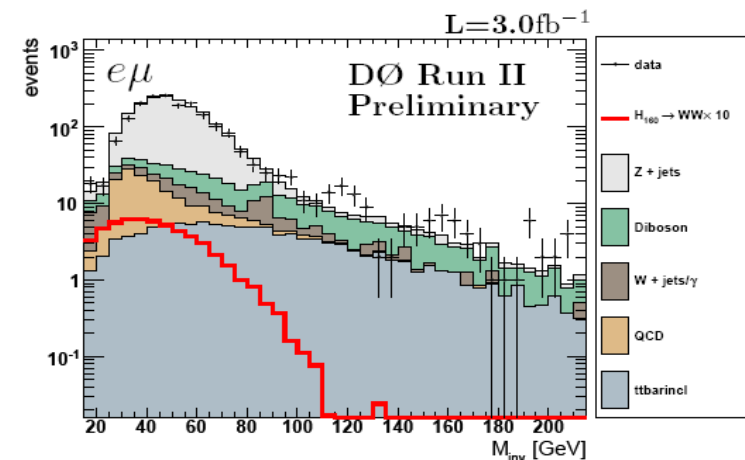
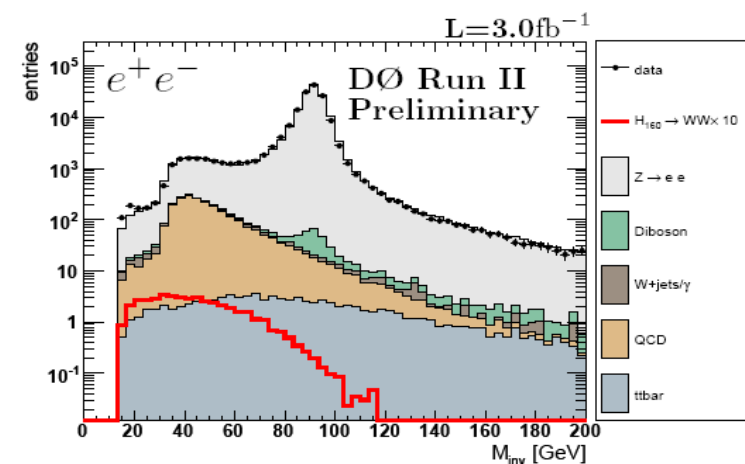
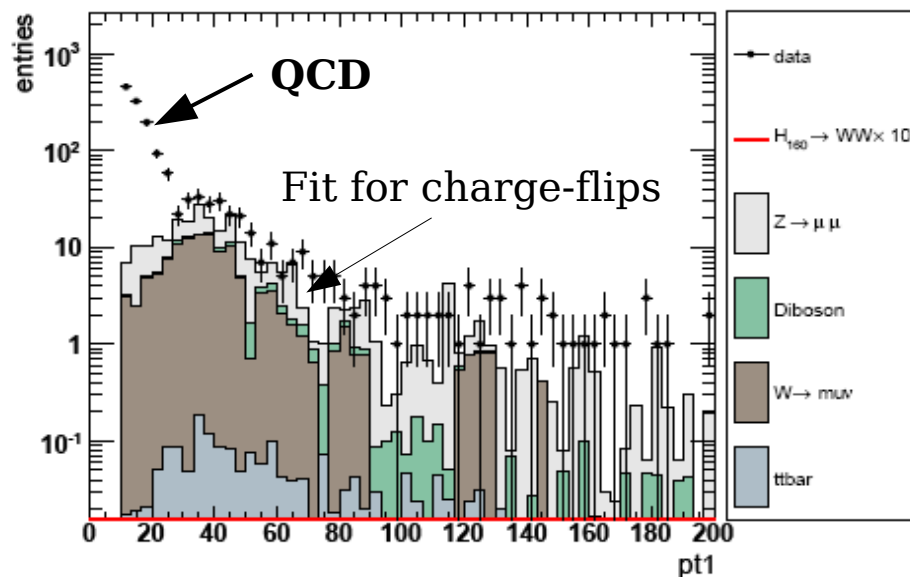
3.0/fb

Dominates sensitivity for $m_H > \sim 135$ GeV

Select di-lepton events ($\sim 100\%$ trigger eff.)

Study and compare to $Z \rightarrow ee, \mu\mu, \tau\tau(\rightarrow e\mu)$

QCD determined from like-sign data
(accounting for other backgrounds)



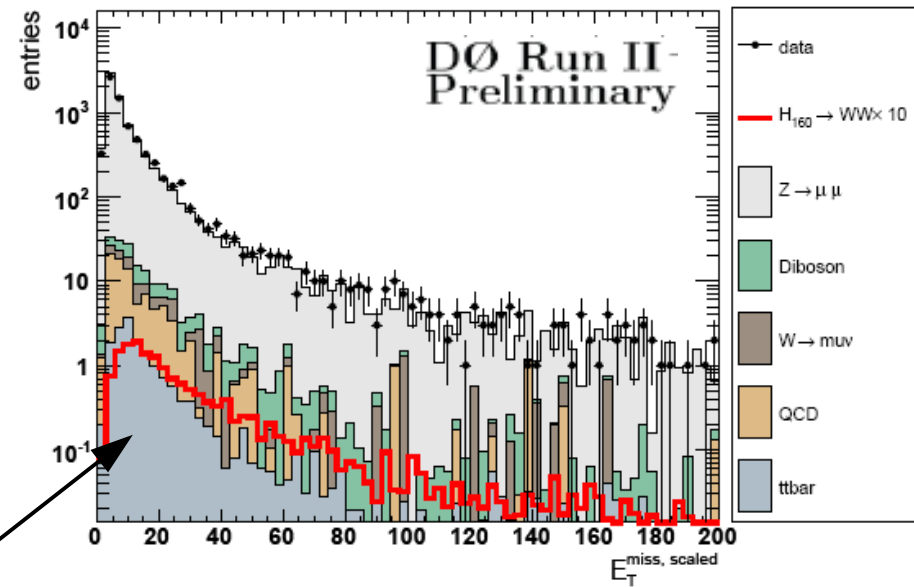
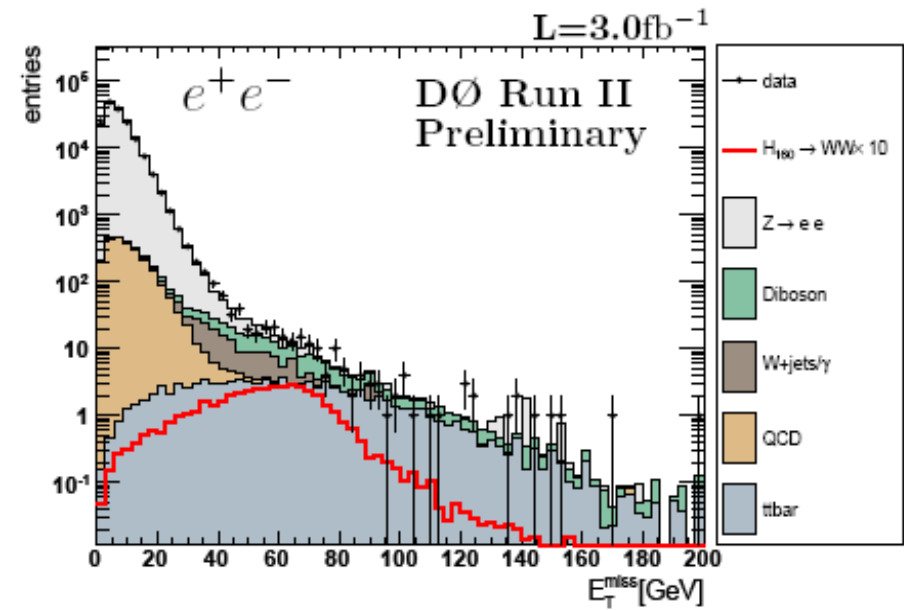
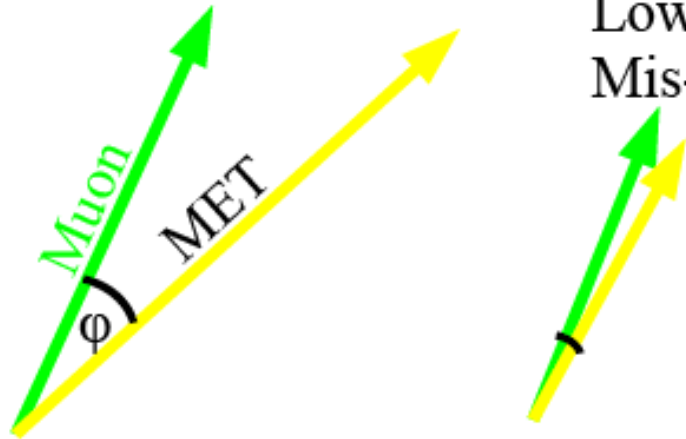
$$H \rightarrow WW \rightarrow l\nu l\nu$$

Signal has large ME_T and ME_T *significance*

ME_T is not aligned with either lepton

High transverse mass:
Real W event

Low transverse mass:
Mis-measured muon



$$E_T^{\text{Scaled}} = \frac{E_T}{\sqrt{\sum_{\text{jets}} (\Delta E^{\text{jet}} \cdot \sin \theta^{\text{jet}} \cdot \cos \Delta \phi (\text{jet}, E_T))^2}}$$

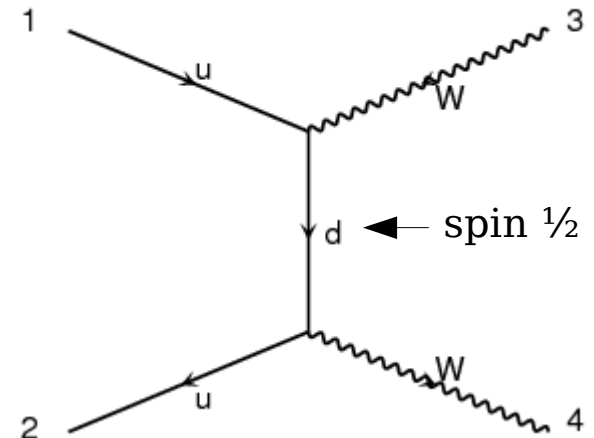
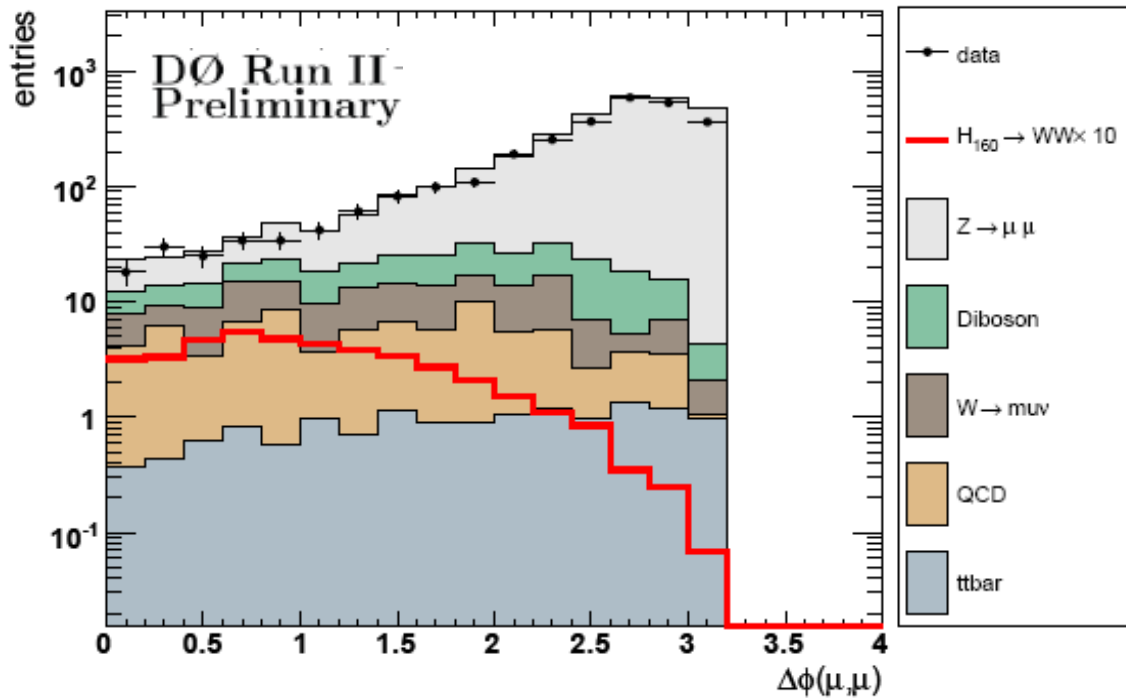
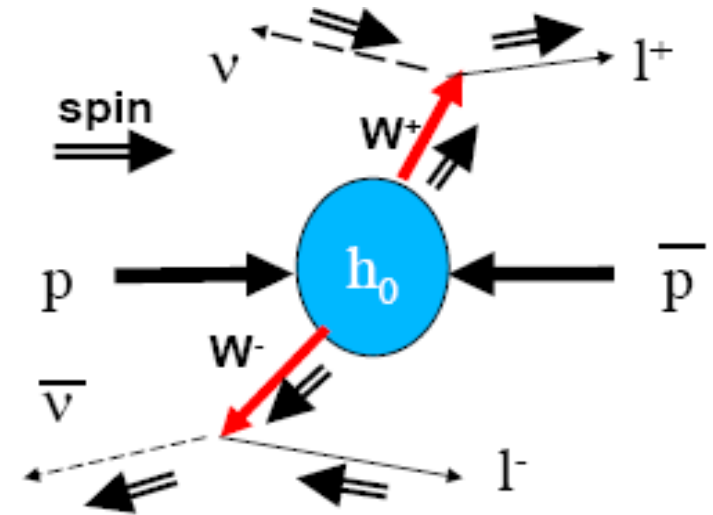
*MET projected
onto jet direction*

$$H \rightarrow WW \rightarrow l\nu l\nu$$

**Higgs is a scalar,
leptons are more aligned**

$qq \rightarrow WW$ (spin $\frac{1}{2}$ quark, spin 1 boson),
leptons are less aligned

$Z \rightarrow ll$ is also back-to-back, not aligned



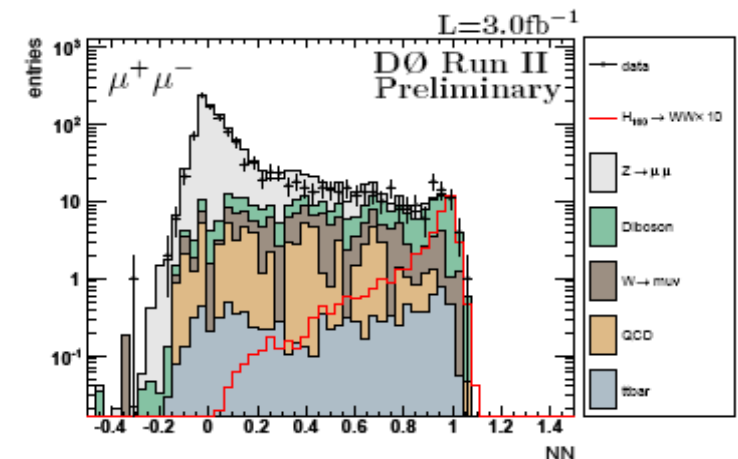
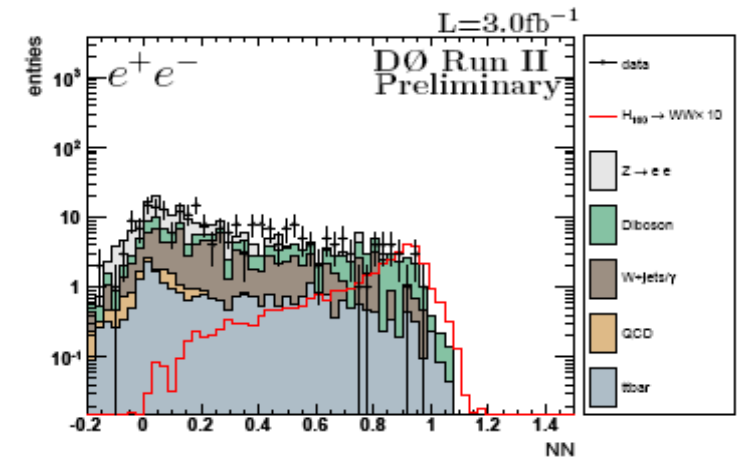
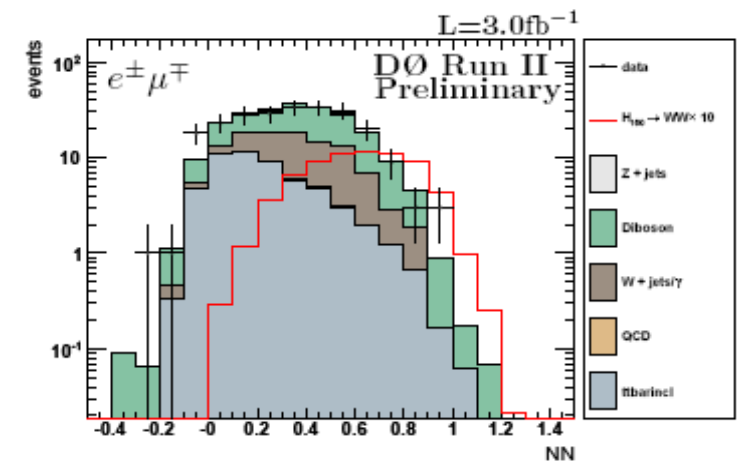
$$H \rightarrow WW \rightarrow l\nu l\nu$$

Artificial Neural Net used to separate signal

- Trained against weighted sum of all backgrounds
- Each lepton channel independently
- Each mass (every 5 GeV) independently

~30% more sensitive than cut-based analysis

Object Variables	Event Var	Topo Var
P_T^{l1} & P_T^{l2}	$M_{inv}(l,l)$	$\Delta\phi(l,l)$
Σ lepton P_T	$M_t^{\min}(1, E_T)$	$\Delta\phi(E_T, l_1)$
Σ jet P_T (H_T)	E_T	$\Delta\phi(E_T, l_2)$
Lepton Quality	E_t^{scalar}	



$H \rightarrow WW \rightarrow l\nu l\nu$

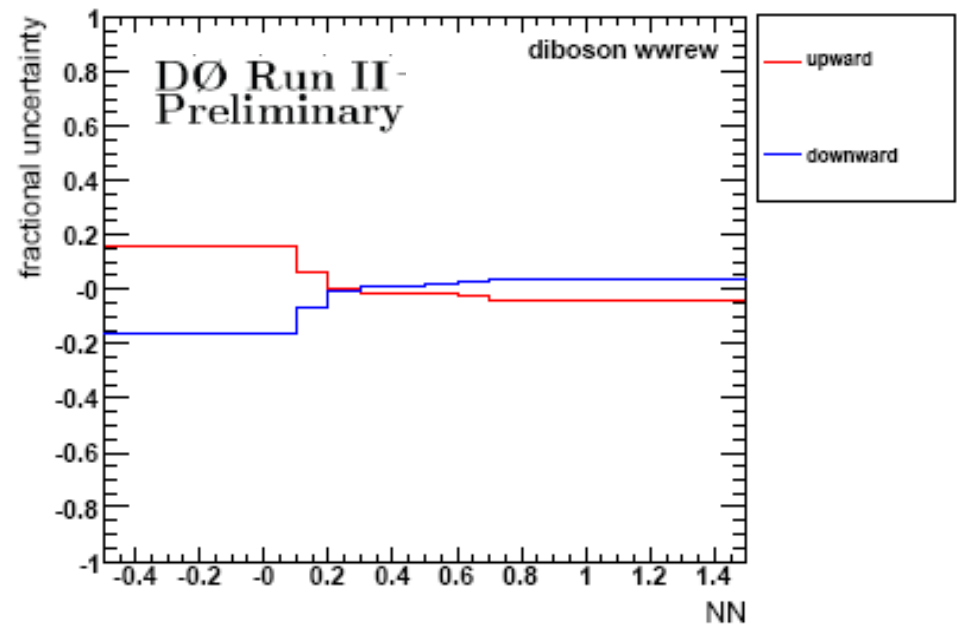
Flat systematics:

- Lepton efficiencies (2-8%)
- Lepton momentum scale (2%)
- Theoretical cross-sections (7-10%)
- Jet $\rightarrow$ lepton fake rate (10%)
- QCD normalization (30%)

Shape systematics (on NN output):

- Jet efficiency (6%)
- Jet energy scale (7%)
- Jet energy resolution (3%)
- Inst. luminosity (0.3%)
- Interaction region (1%)
- Di-boson p_T (5%) $\longrightarrow$

Change in NN output when changing WW p_T

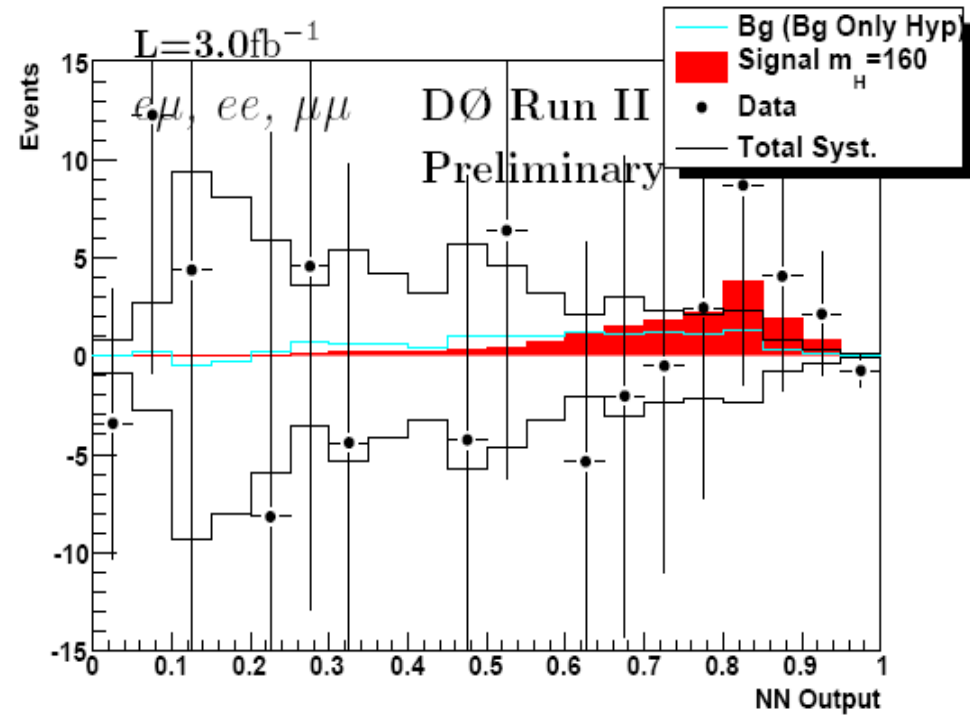
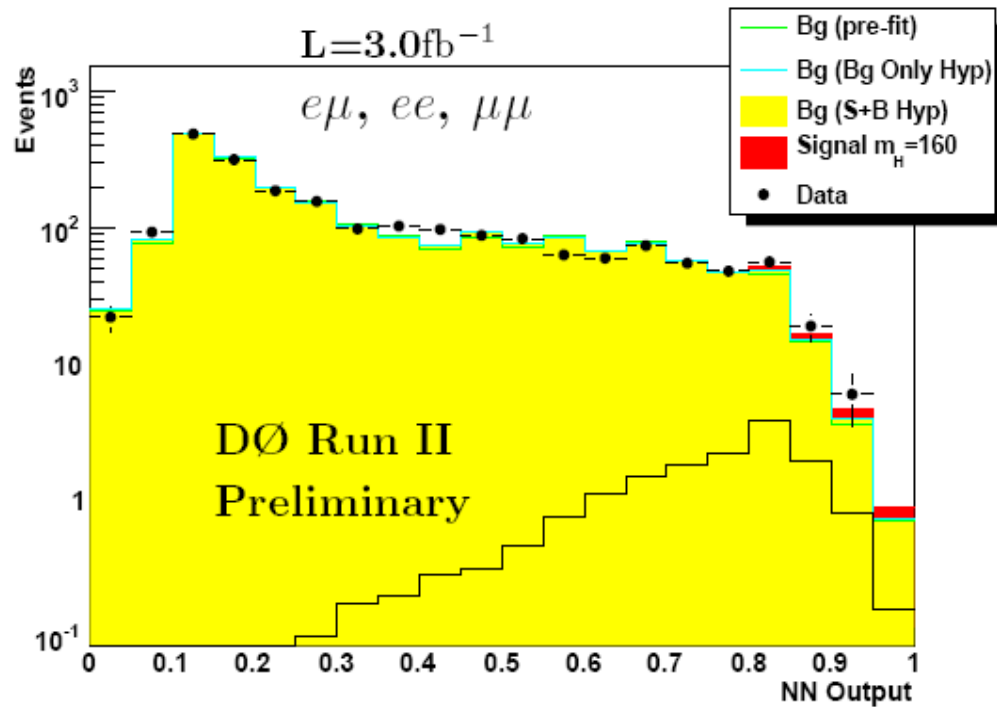


$H \rightarrow WW \rightarrow l\nu l\nu$

Backgrounds are large!

Systematics under control

- but further understanding will improve sensitivity

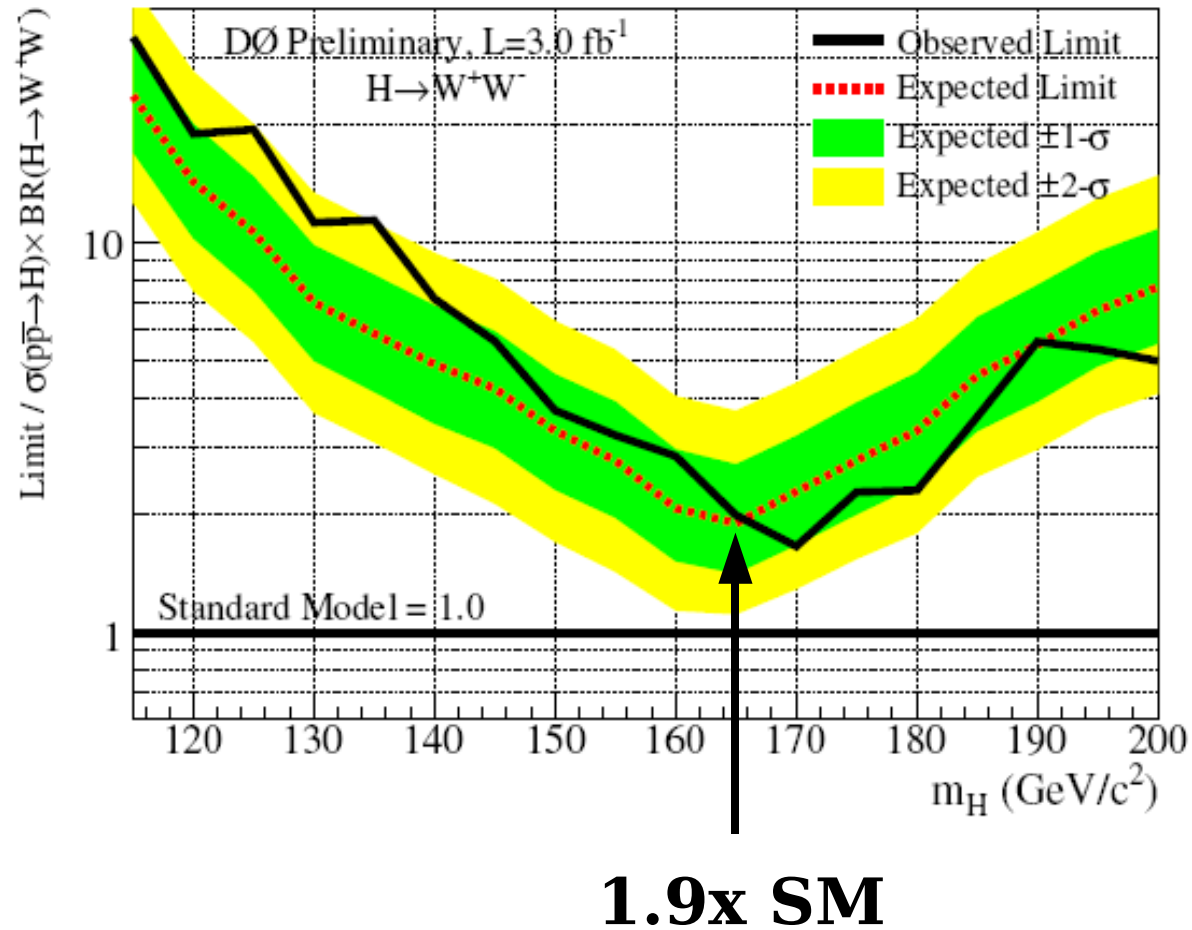
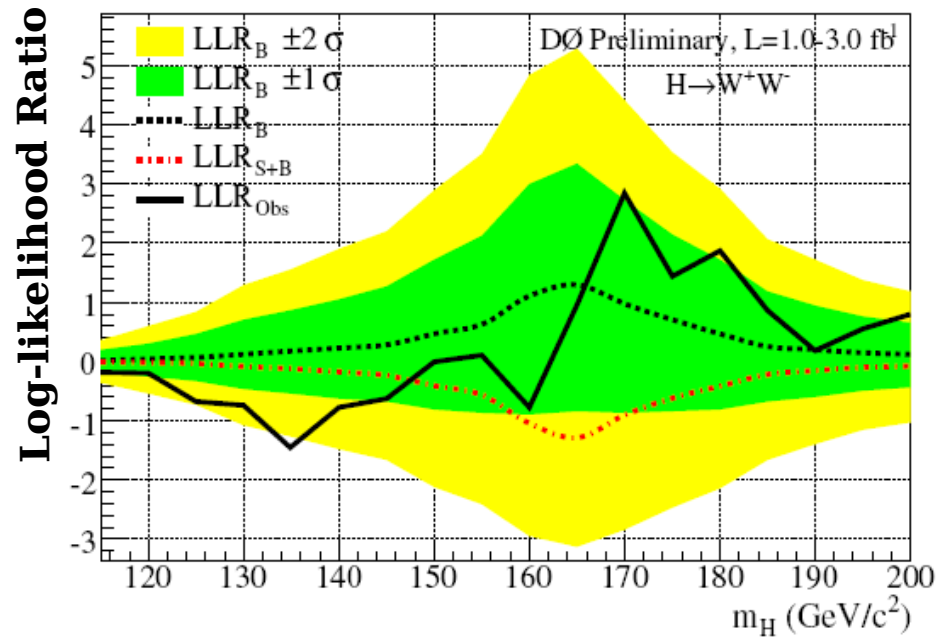


$H \rightarrow WW \rightarrow l\nu l\nu$

Outputs of NNs used to
set limits at 95% CL
every 5 GeV

CL_s method (a la LEP II)

Good data/SM agreement



DØ Higgs Combination

Large number of individual channels

Systematics are properly correlated between channels where appropriate

Channel	Data Epoch	Luminosity (fb^{-1})	Final Variable
$WH \rightarrow e\nu b\bar{b}$, ST/DT, $W + 2$ jet	Run IIa	1.1	NN discriminant
$WH \rightarrow e\nu b\bar{b}$, ST/DT, $W + 3$ jet	Run IIa	1.1	Dijet Mass
$WH \rightarrow e\nu b\bar{b}$, ST/DT, $W + 2$ jet	Run IIb	0.6	NN discriminant
$WH \rightarrow \mu\nu b\bar{b}$, ST/DT, $W + 2$ jet	Run IIa	1.1	NN discriminant
$WH \rightarrow \mu\nu b\bar{b}$, ST/DT, $W + 3$ jet	Run IIa	1.1	Dijet Mass
$WH \rightarrow \mu\nu b\bar{b}$, ST/DT, $W + 2$ jet	Run IIb	0.6	NN discriminant
$WH \rightarrow \ell\nu b\bar{b}$, DT	Run IIa	0.9	DTree discriminant
$WH \rightarrow \ell\nu b\bar{b}$, DT	Run IIb	1.2	DTree discriminant
$ZH \rightarrow \nu\bar{\nu} b\bar{b}$, DT	Run IIa	0.9	DTree discriminant
$ZH \rightarrow \nu\bar{\nu} b\bar{b}$, DT	Run IIb	1.2	DTree discriminant
$ZH \rightarrow e^+e^- b\bar{b}$, ST/DT	Run IIa	1.1	NN discriminant
$ZH \rightarrow \mu^+\mu^- b\bar{b}$, ST/DT	Run IIa	1.1	NN discriminant
$ZH \rightarrow e^+e^- b\bar{b}$, ST/DT	Run IIb	1.2	NN discriminant
$ZH \rightarrow \mu^+\mu^- b\bar{b}$, ST/DT	Run IIb	1.2	DTree discriminant
$WH \rightarrow WW^+W^- (\mu^\pm\mu^\pm)$	Run IIa	1.1	2-D Likelihood
$WH \rightarrow WW^+W^- (e^\pm\mu^\pm)$	Run IIa	1.1	2-D Likelihood
$WH \rightarrow WW^+W^- (e^\pm e^\pm)$	Run IIa	1.1	2-D Likelihood
$H \rightarrow W^+W^- (\mu^+\mu^-)$	Run IIa+Run IIb	3.0	NN discriminant
$H \rightarrow W^+W^- (e^\pm\mu^\mp)$	Run IIa+Run IIb	3.0	NN discriminant
$H \rightarrow W^+W^- (e^+e^-)$	Run IIa+Run IIb	3.0	NN discriminant
$H \rightarrow \gamma\gamma$	Run IIa+Run IIb	2.7	Di-photon Invariant Mass

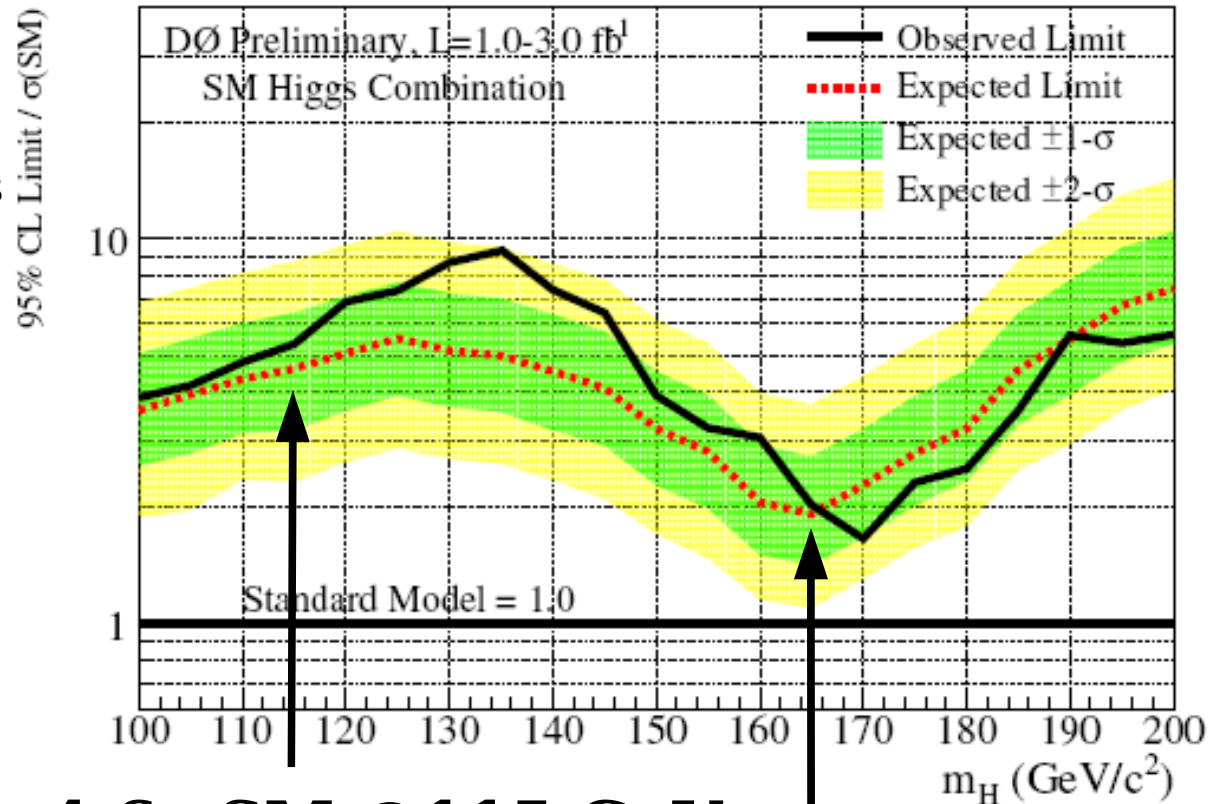
DØ Higgs Combination

To improve:

- More data
- Advanced analysis techniques
- Lepton ID / acceptance
- Include additional channels
- Lower systematics
- ...

And particularly at low mass:

- Better b-tagging
 - b/c separation
 - $g \rightarrow bb$ / bb separation
 - muon tagging
 - ...
- **Jet / b-jet resolution**



4.6x SM @115 GeV

1.9x SM @165 GeV

Jet and b-jet Resolution

Critical for low-mass $h \rightarrow b\bar{b}$ searches

- Aiming for 20% improvement

Multiple jet energy corrections

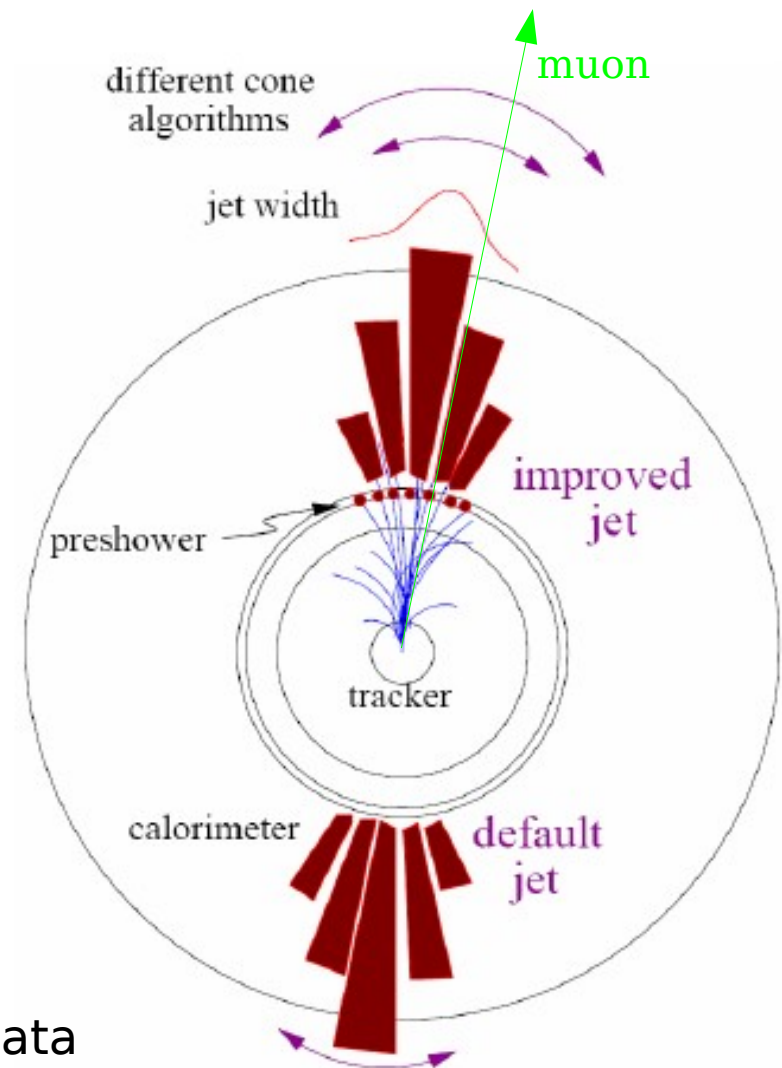
- Jet-width dependence
- Jet cone radii
- Pre-shower energy
- Track-based
- ...

And b-jet specific corrections

- b-jet energy scale
- Semi-leptonic decays
- ...

And methods for *measuring* b-jet resolution in data

- $\gamma + b\text{-jet}$, $Z + b\text{-jet}$, di-b-jet balancing



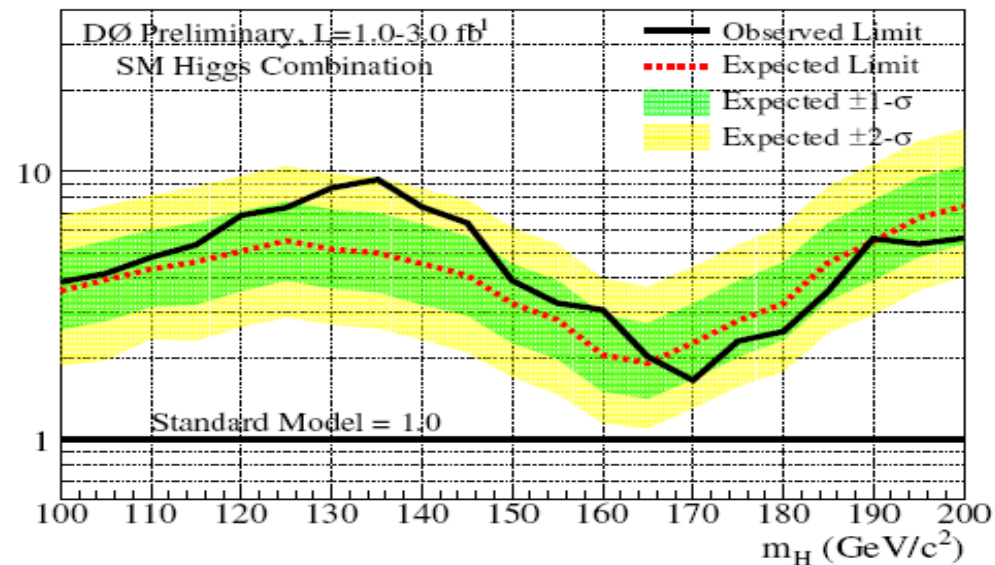
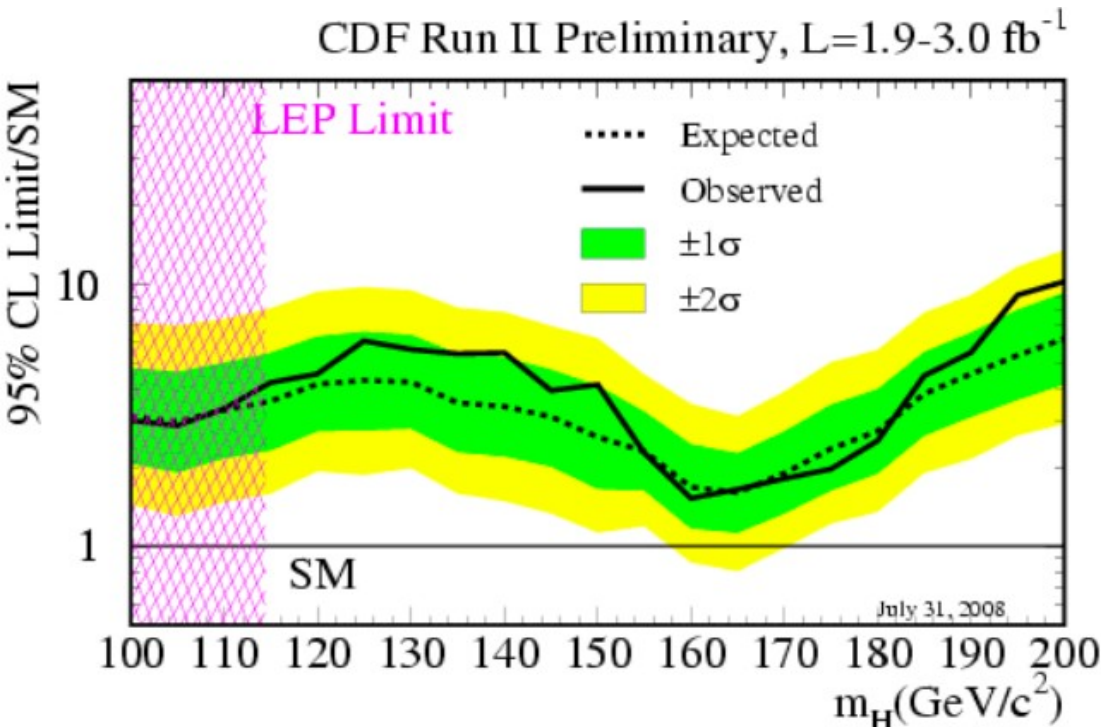
Tevatron Higgs Combination

CDF uses Bayesian limit-setting technique (cross-checked by DØ CL_s)

Systematic uncertainties properly correlated between experiments

Low-mass combination (<155 GeV) not yet updated... ~70 channels!

Expected sensitivity <3x SM @115 GeV



Tevatron Higgs Combination

SM Higgs excluded at 170 GeV !!!

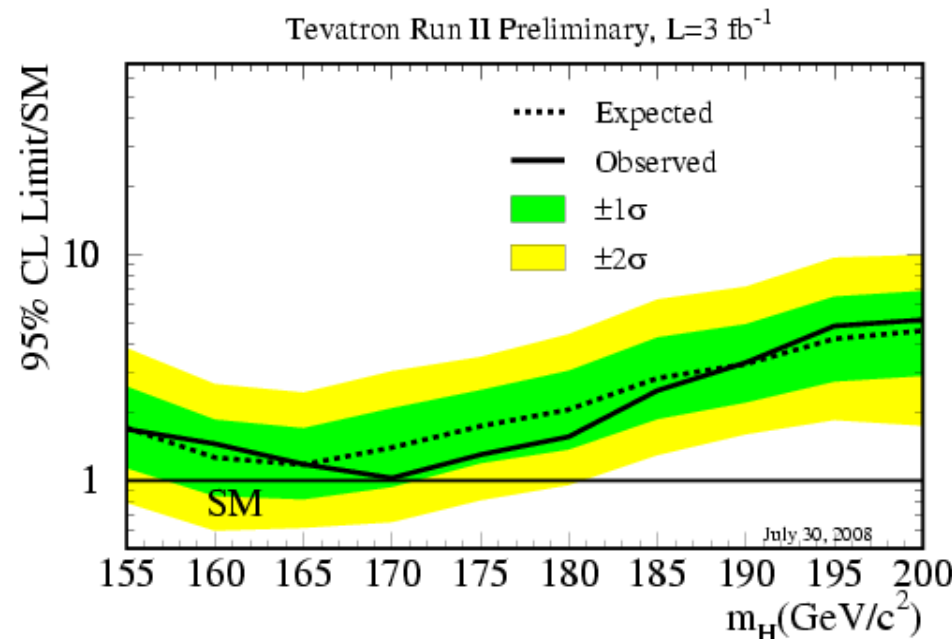
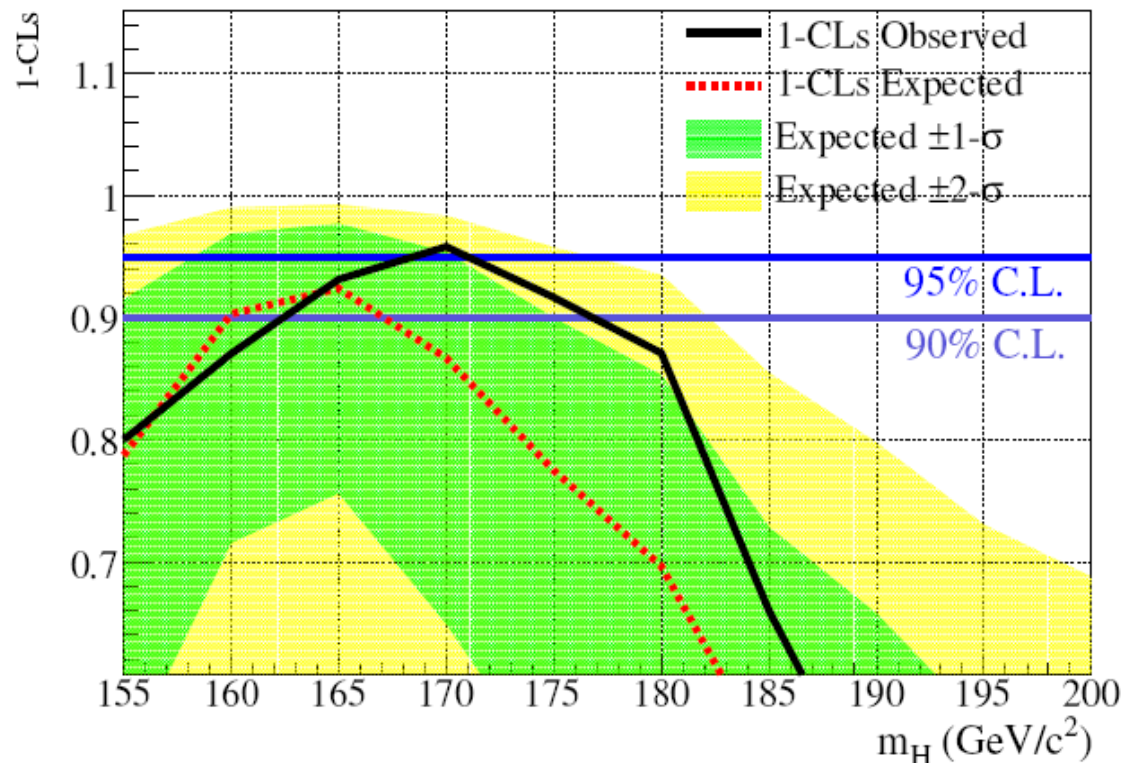
Sensitive to a large range of Higgs masses by Moriond

Verified using two calculations



95%CL Limits/SM

$M_Higgs(GeV)$	160	165	170	175
Method 1: Exp	1.3	1.2	1.4	1.7
Method 1: Obs	1.4	1.2	1.0	1.3
Method 2: Exp	1.2	1.1	1.3	1.7
Method 2: Obs	1.3	1.1	0.95	1.2



SUSY Higgs

Supersymmetry predicts (at least) **5 Higgs**

- cancel anomalies

h/H and A typically degenerate: ϕ

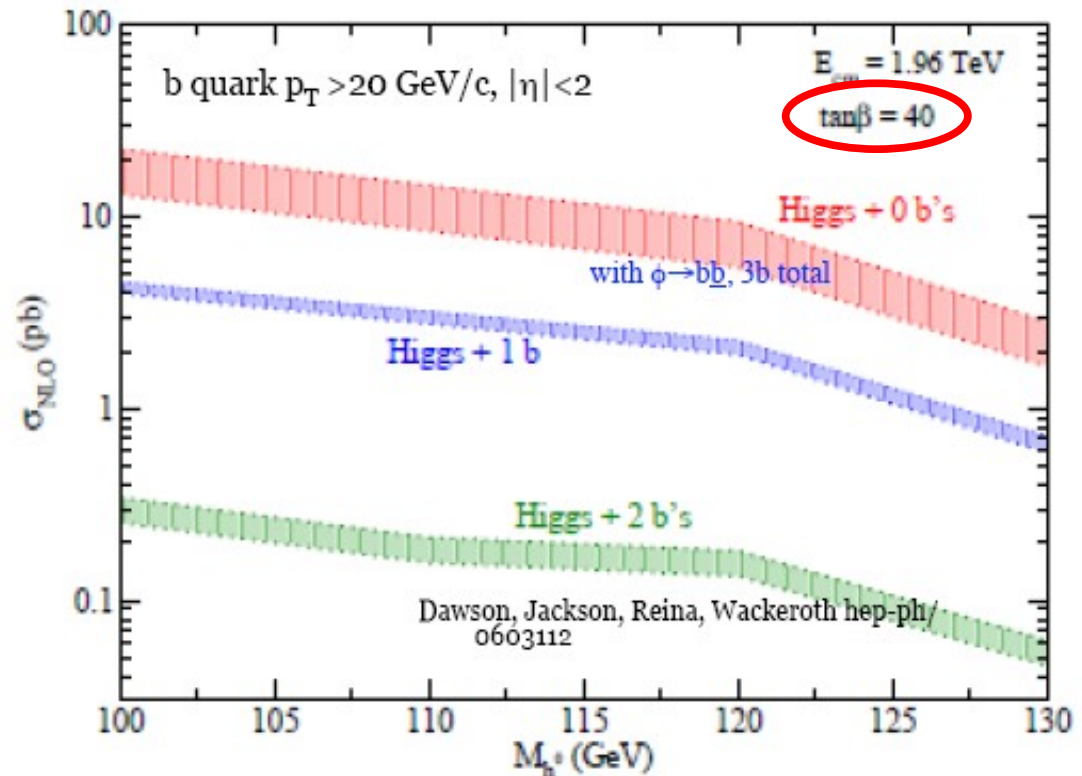
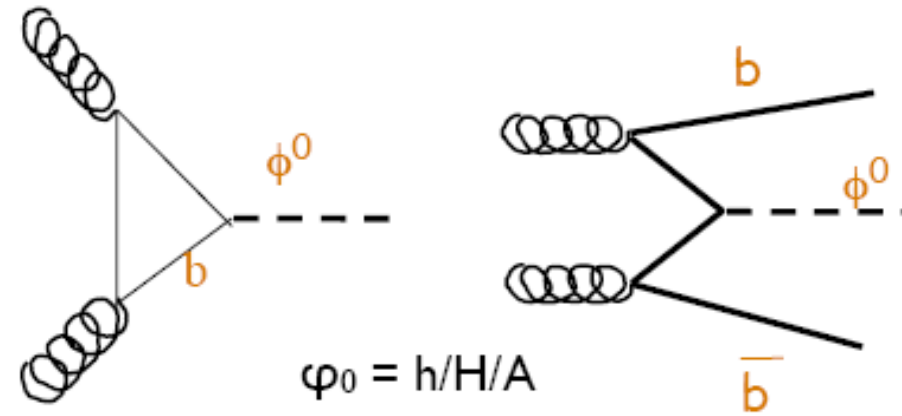
Cross-section proportional to $\tan^2\beta$

- $\sim 1000x$ enhancement possible!

$\tan\beta \sim 40$ is well-motivated (m_t/m_b)

Dominant decays:

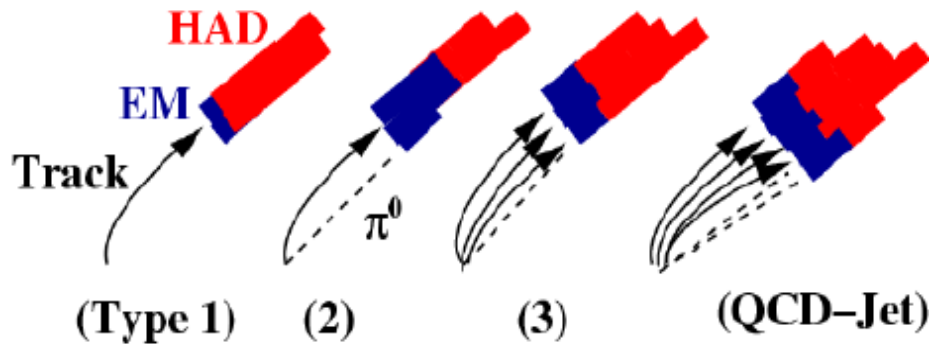
- **bb (90%)**
- **$\tau\tau$ (10%)**



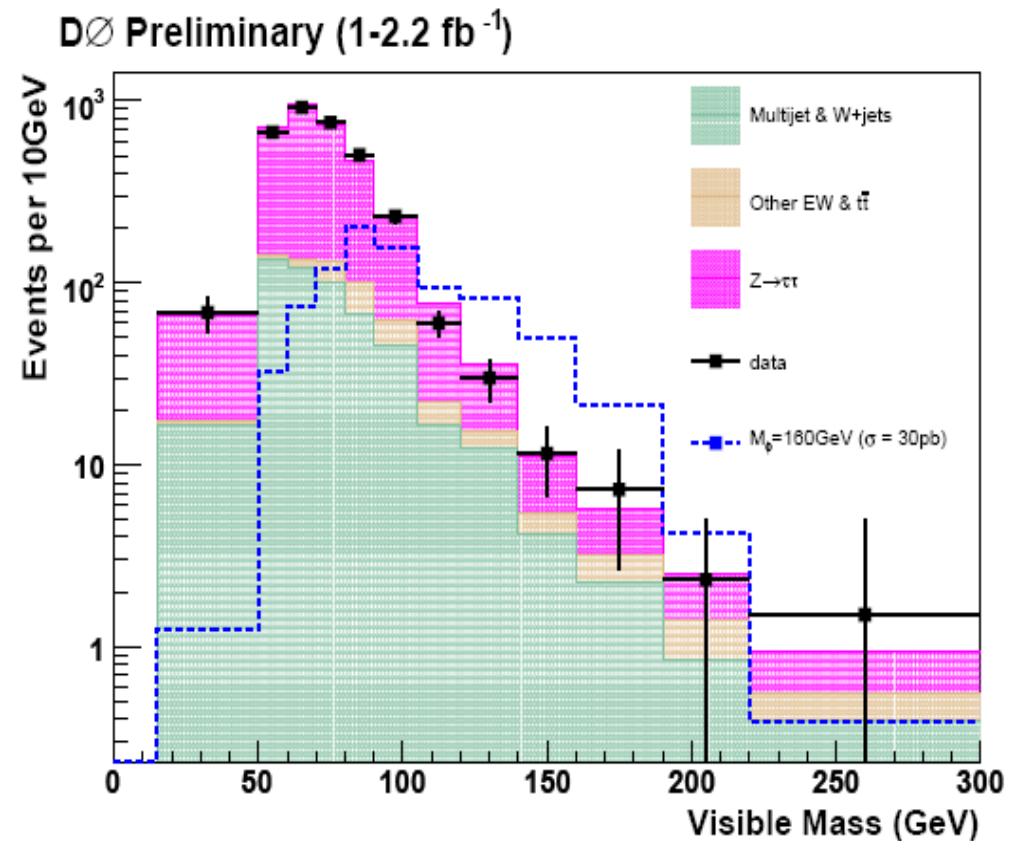
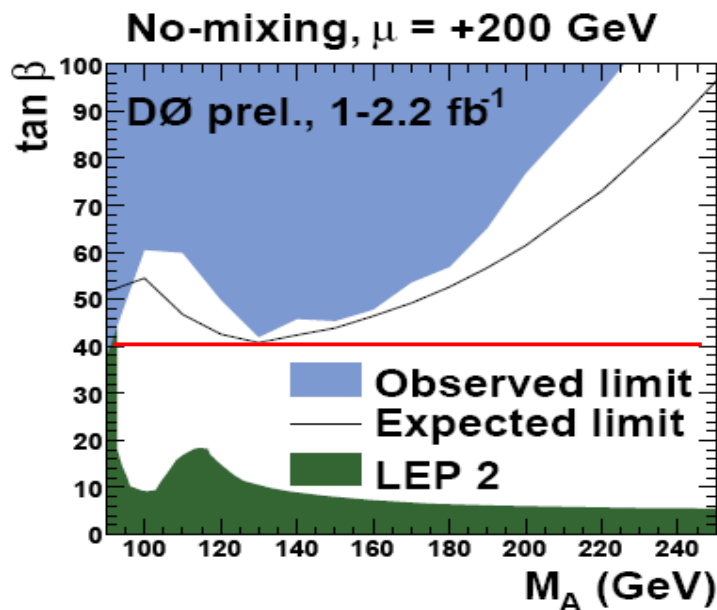
$$\phi \rightarrow \tau\tau$$

Single-lepton trigger, look for $\mu + \tau_{\text{had}}$, $e + \tau_{\text{had}}$, $\mu + e$

Reconstruct hadronic taus and reject jets



arXiv:0805.2491



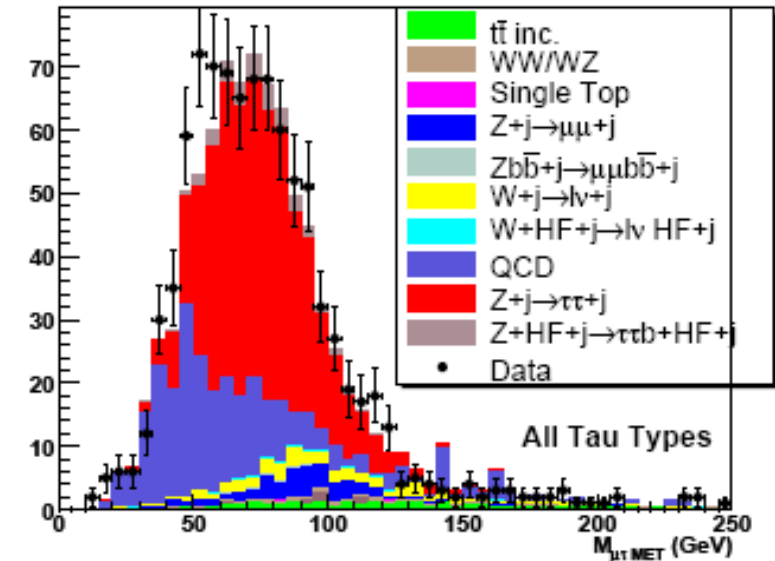
$$b\bar{b} \rightarrow b\tau\tau$$

Select $\mu + \tau_{\text{had}} + \text{jet}$ events

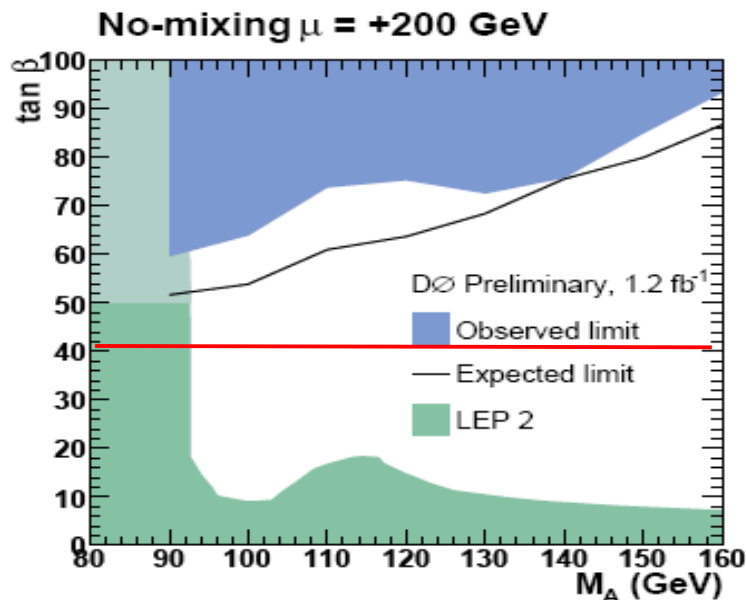
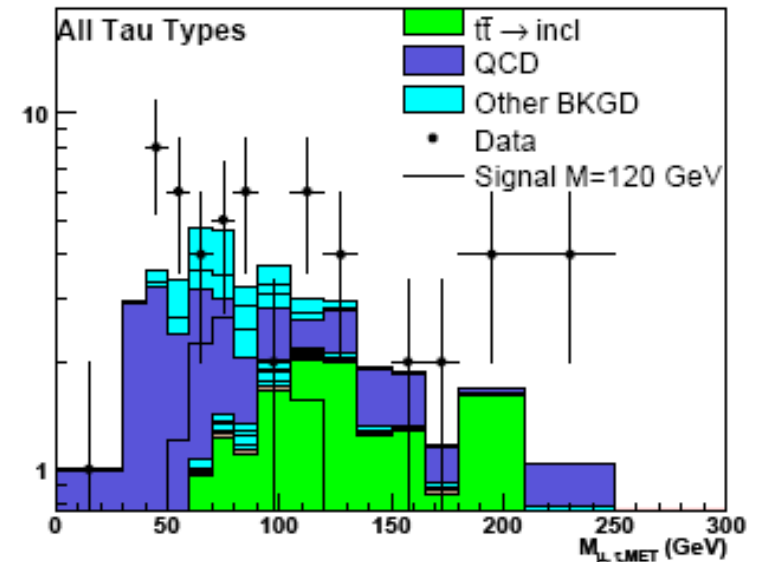
Apply b-jet tagging

Look at $\mu + \tau_{\text{had}} + M_{E_T}$ invariant mass

DØ RunII Preliminary, 1.2 fb⁻¹



DØ RunII Preliminary, 1.2 fb⁻¹



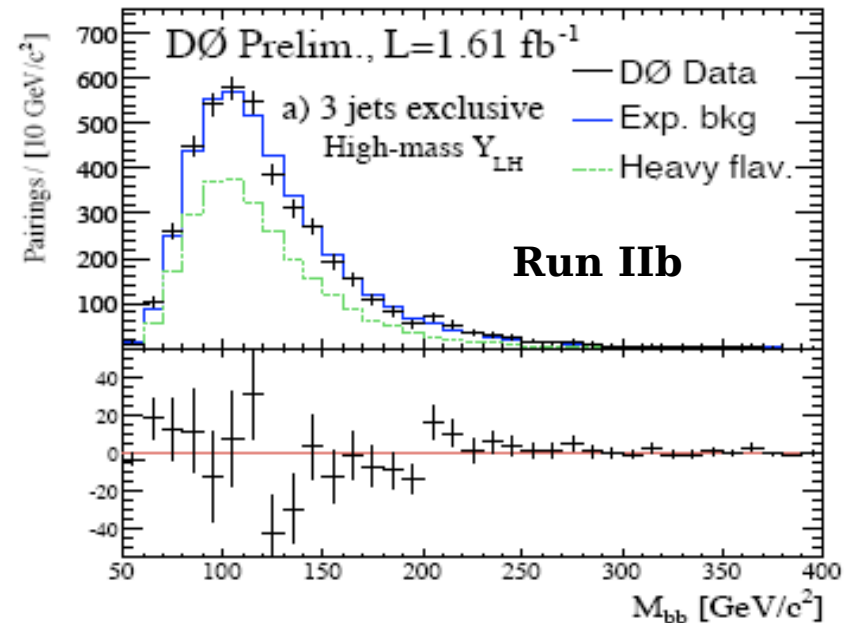
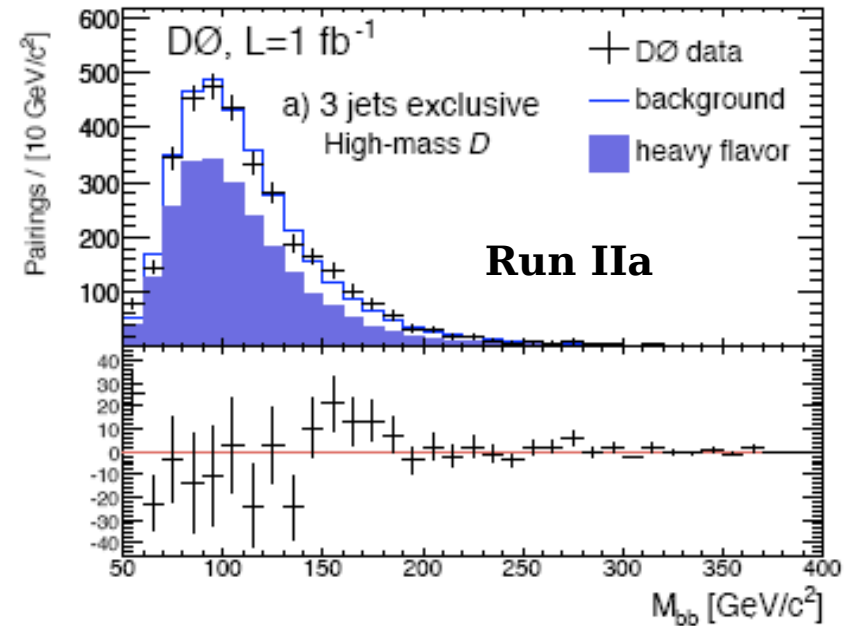
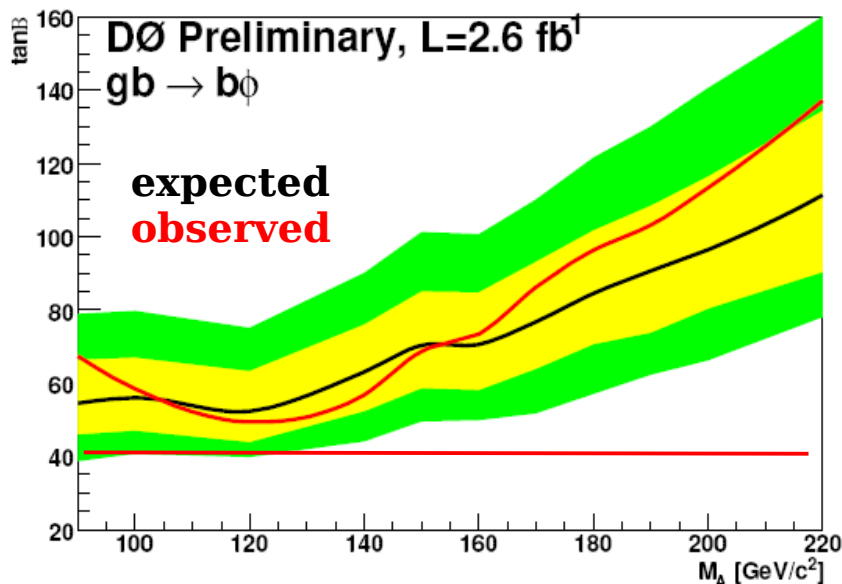
$$b\phi \rightarrow bbb$$

Multi-jet trigger, with b-tagging
Select **triple-b-tagged** events

Background to 3 b-tagged signal derived
from 2 b-tagged data

Correct for 2→3 kinematic bias from detailed
MC ALPGEN simulation of bbjj,bbcc,bbbb

arXiv:0805.3556



Conclusions

DØ is running great, and closing in on the Higgs !

Already becoming sensitive to the SM Higgs at high mass (~ 165 GeV)

Expect low mass Higgs sensitivity as well with full Tevatron dataset
(and analysis improvements)

Excellent sensitivity to SUSY Higgs at high $\tan\beta$, now approaching $\tan\beta \sim 40$
– Combination underway

Next talk will discuss the combination with CDF...

Conclusions

The Tevatron is closing in on the Higgs

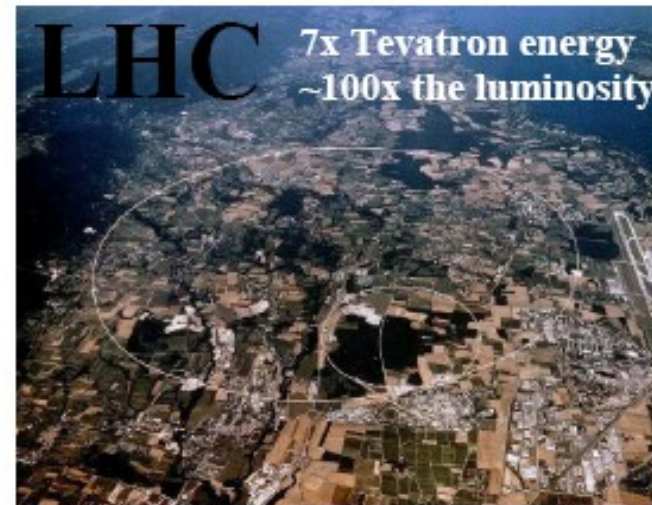
Consistent with EW fits, we have direct evidence against a heavy Higgs...

SM Higgs excluded at 170 GeV !!!

Expect low mass Higgs sensitivity as well with full Tevatron dataset
(and analysis improvements)

Excellent sensitivity to SUSY Higgs at high $\tan\beta$, now approaching $\tan\beta \sim 40$
– Combinations underway

**The Tevatron is small,
but doing a mighty job!**



Backup

$$H \rightarrow WW \rightarrow l\nu l\nu$$

All pre-selections kept as loose as possible

- Cut out regions with almost no signal
- Cut out regions that could not be well modeled

Final state	$e\mu$	ee	$\mu\mu$
Cut 0 Pre-selection	lepton ID, leptons with opposite charge and $p_T^\mu > 10$ GeV and $p_T^e > 15$ GeV invariant mass $M_{\mu\mu} > 15$ GeV $\mu\mu$: $n_{\text{jet}} < 2$ for $p_T^{\text{jet}} > 15$ GeV and $dR(\mu, \text{jet}) > 0.1$		
Cut 1 Missing Transverse Energy $\cancel{E}_T$ (GeV)	> 20	> 20	> 20
Cut 2 $\cancel{E}_T^{\text{Scaled}}$	> 7	> 6	> 5
Cut 3 $M_T^{\text{min}}(\ell, \cancel{E}_T)$ (GeV)	> 20	> 30	> 20
Cut 4 $\Delta\phi(\mu, \mu)$	< 2.0	< 2.0	< 2.5

$H \rightarrow WW \rightarrow l\nu l\nu$

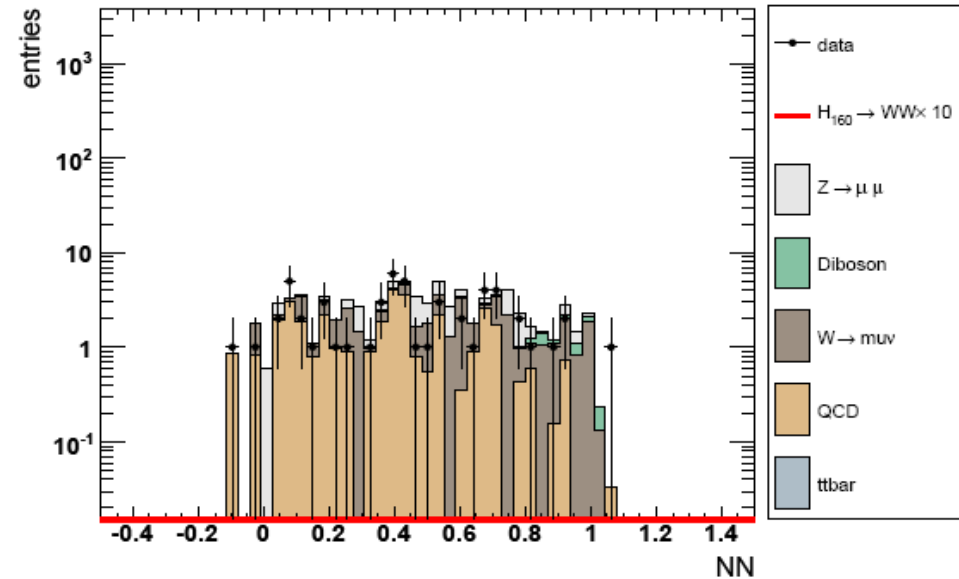
Many cross-checks performed in various other sets of the data/MC

- Like-sign (check W+jets and QCD)
- W+jets selection

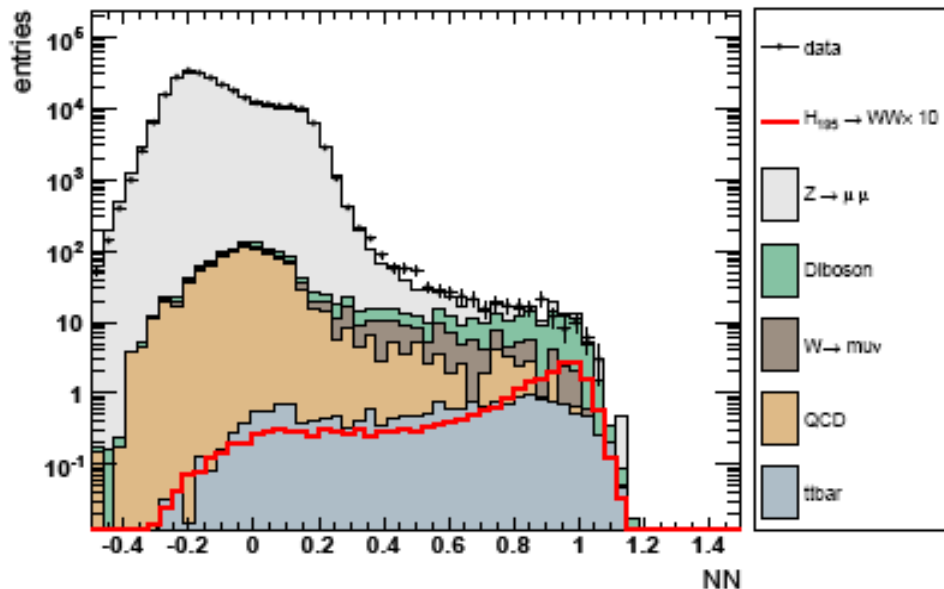
Pre-selection NN output

- Check for correlations not modeled in high-statistics Z samples

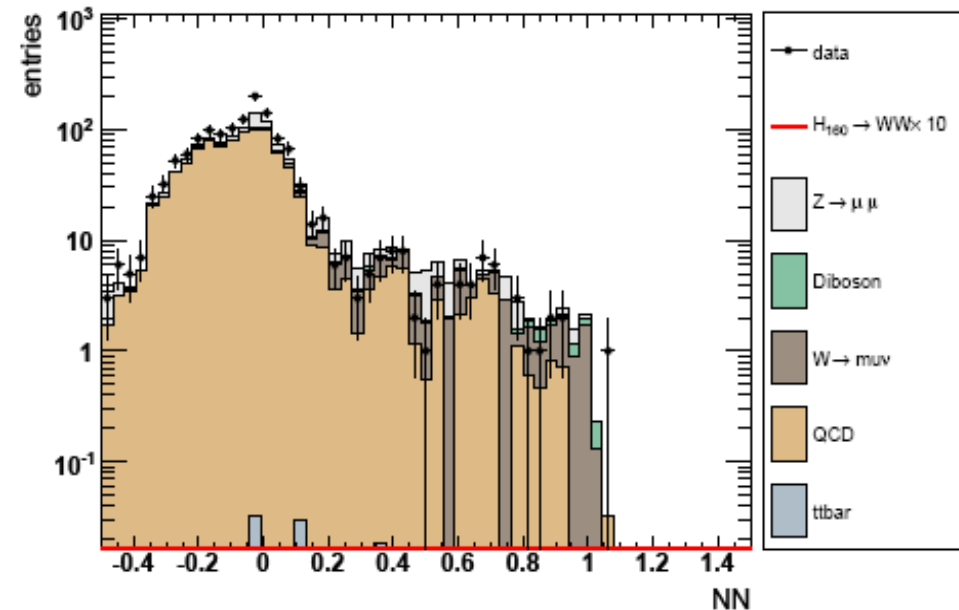
W+jet selection, like-sign



Pre-selection, opposite-sign



Pre-selection, like-sign



Other Models

Could the Higgs be *hiding*?

- Invisible Higgs
- NMSSM: $h \rightarrow aa \rightarrow 4\tau$