Higgs Results

Andy Haas
Columbia University
on behalf of the DØ experiment

CERN Seminar
Sept. 8, 2008

The Higgs Boson

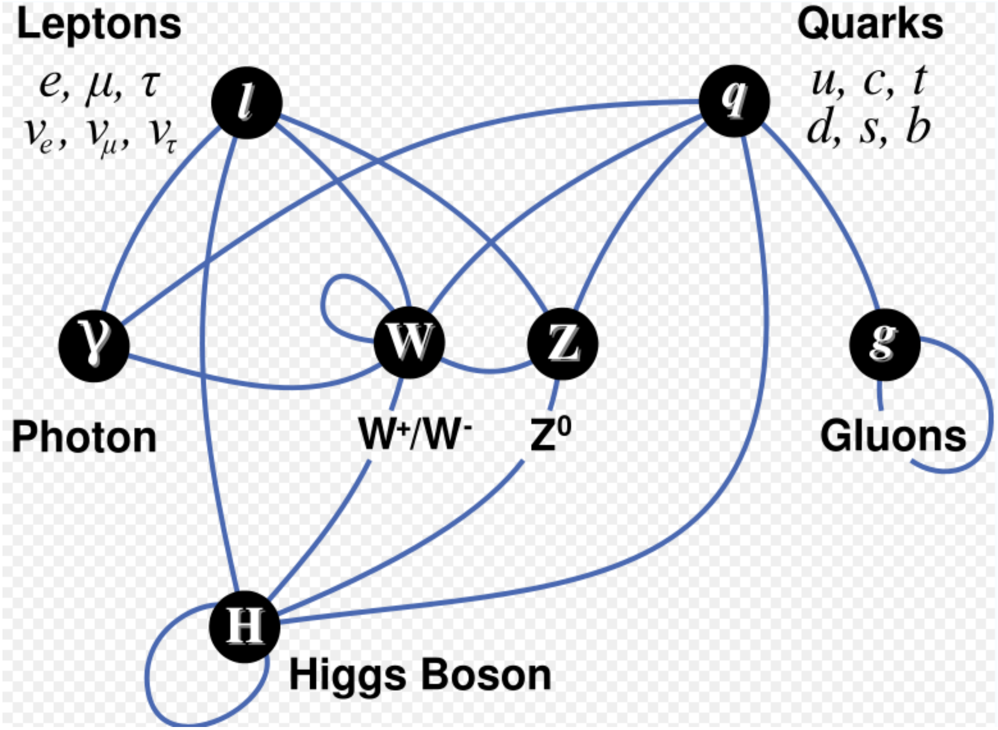
Postulated in the 1960's as a way to give mass to the W/Z bosons

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?

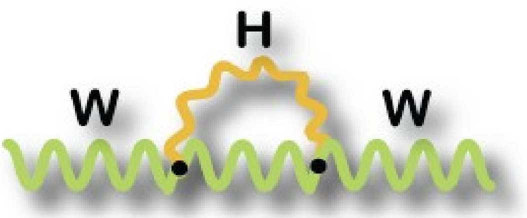
- Why is $m_h << m_{Pl}$? (hierarchy problem)



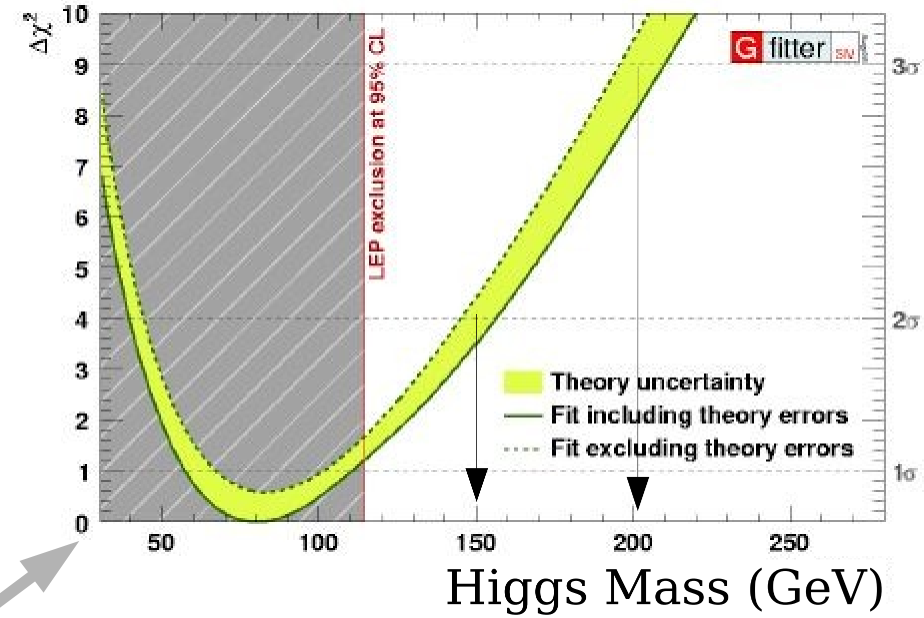
A critical piece of physics we know very little about!

Where's the Higgs?

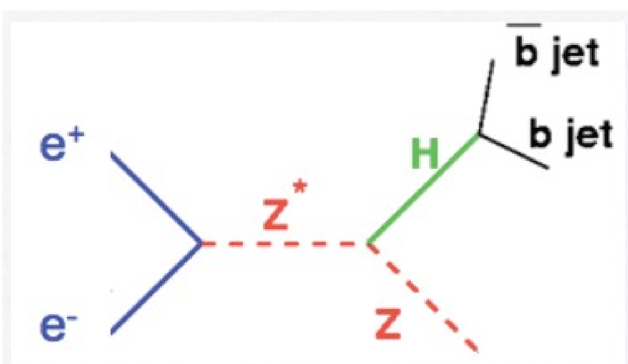
EW variables sensitive to m_H via radiative corrections:



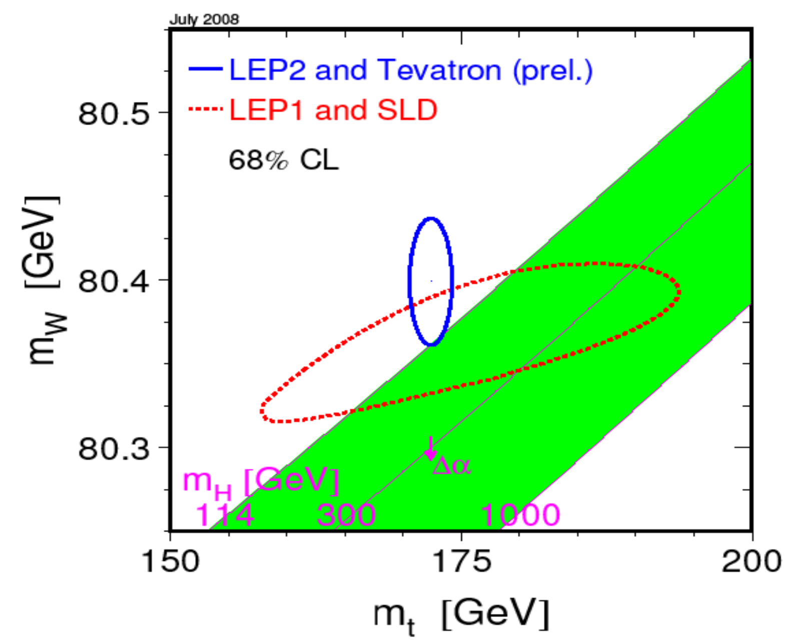
$$\sim \log \frac{m_H}{m_W}$$



LEP II direct: m_H>114.4 GeV



Main LEP channel
(tau also)



DØ and the Tevatron

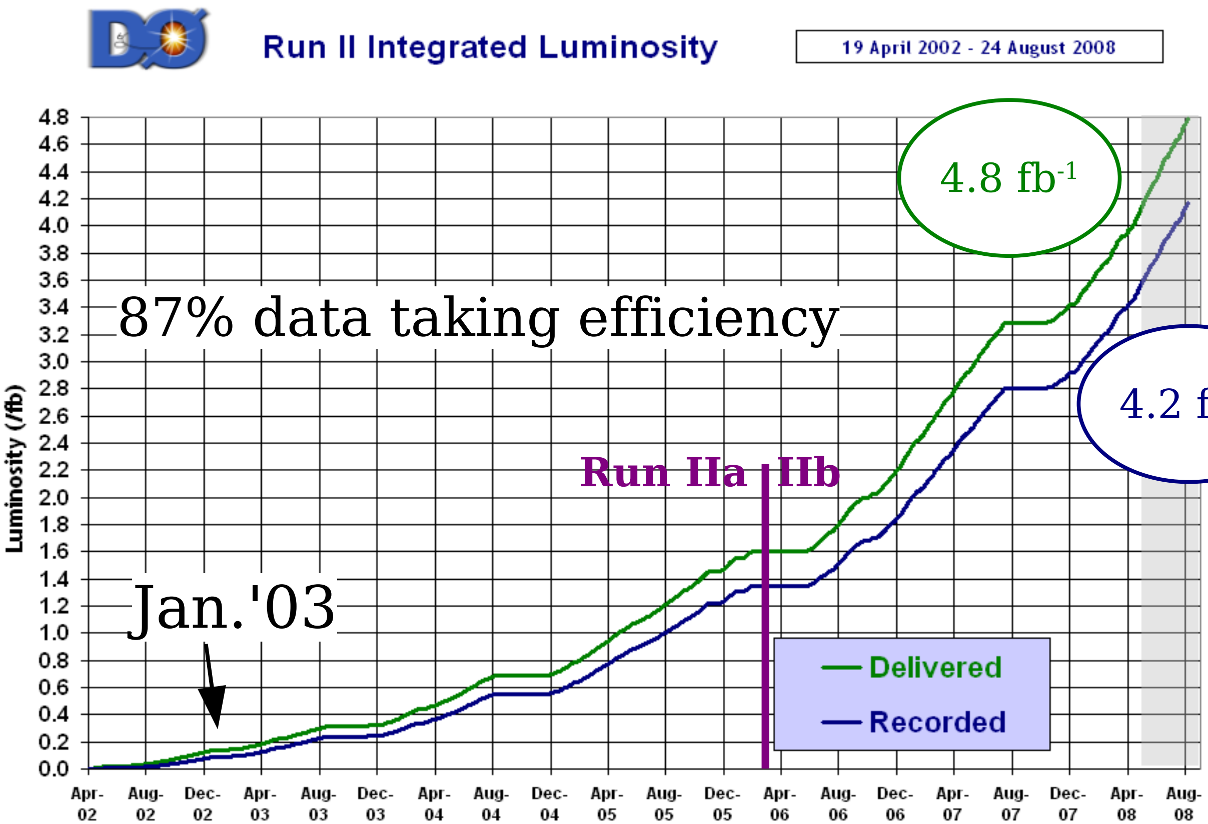
Running (again) since ~2003

p-p*bar*, 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

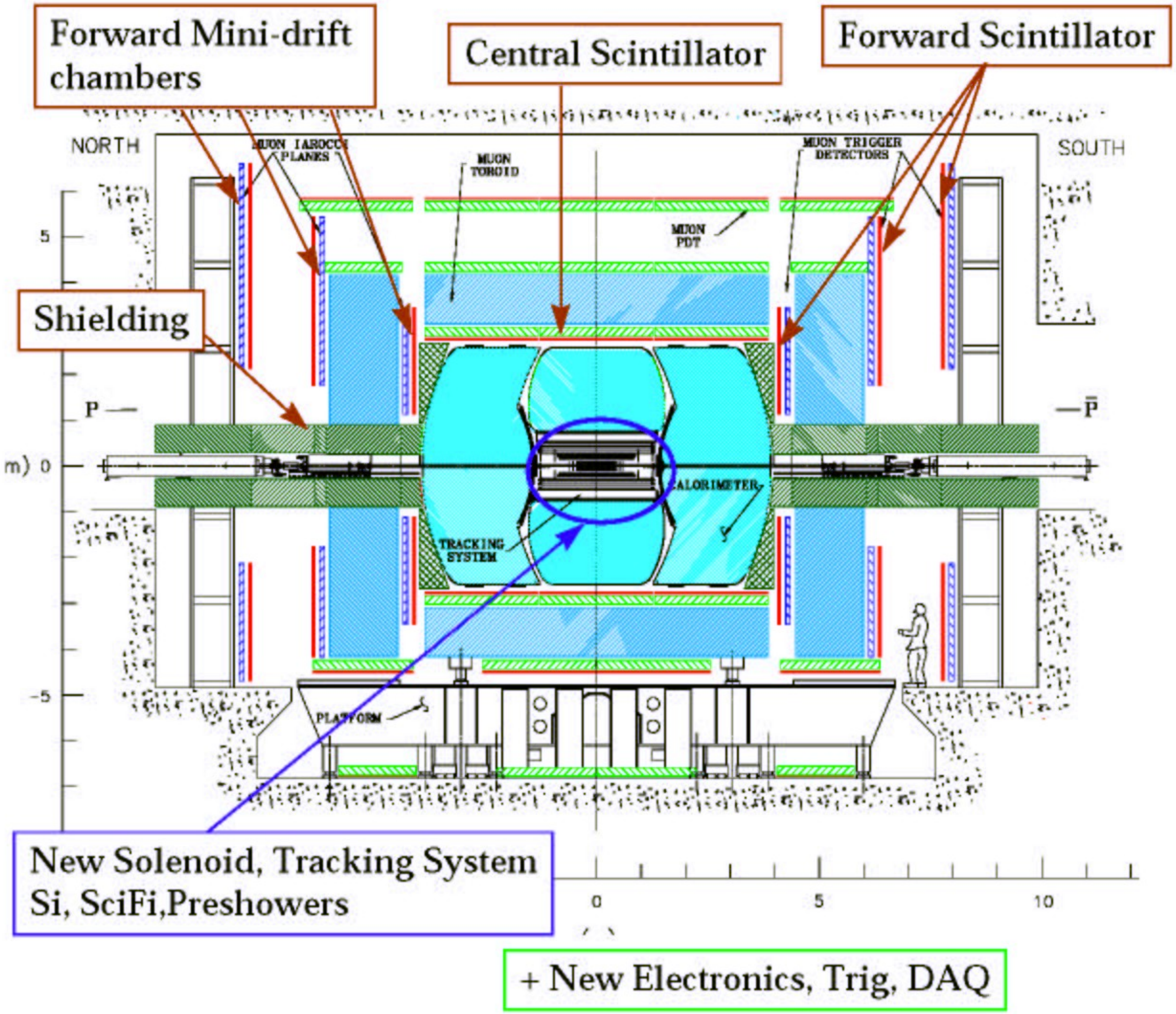
~14% data quality loss, ~75% overall efficiency



Tevatron and DØ both performing very well!

Peak luminosity $>3\times10^{32}\ cm^{-2}s^{-1}$

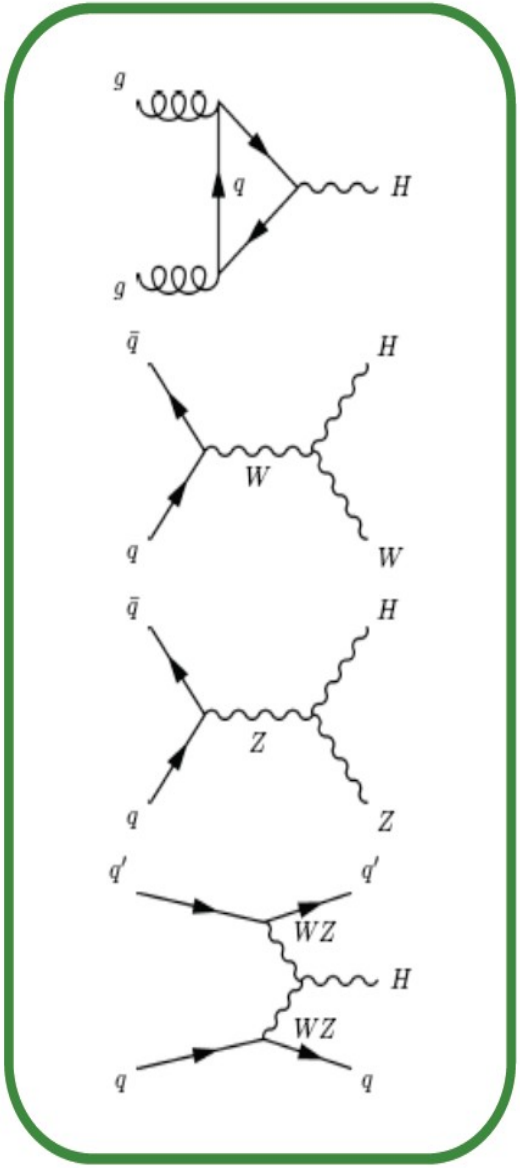
DØ

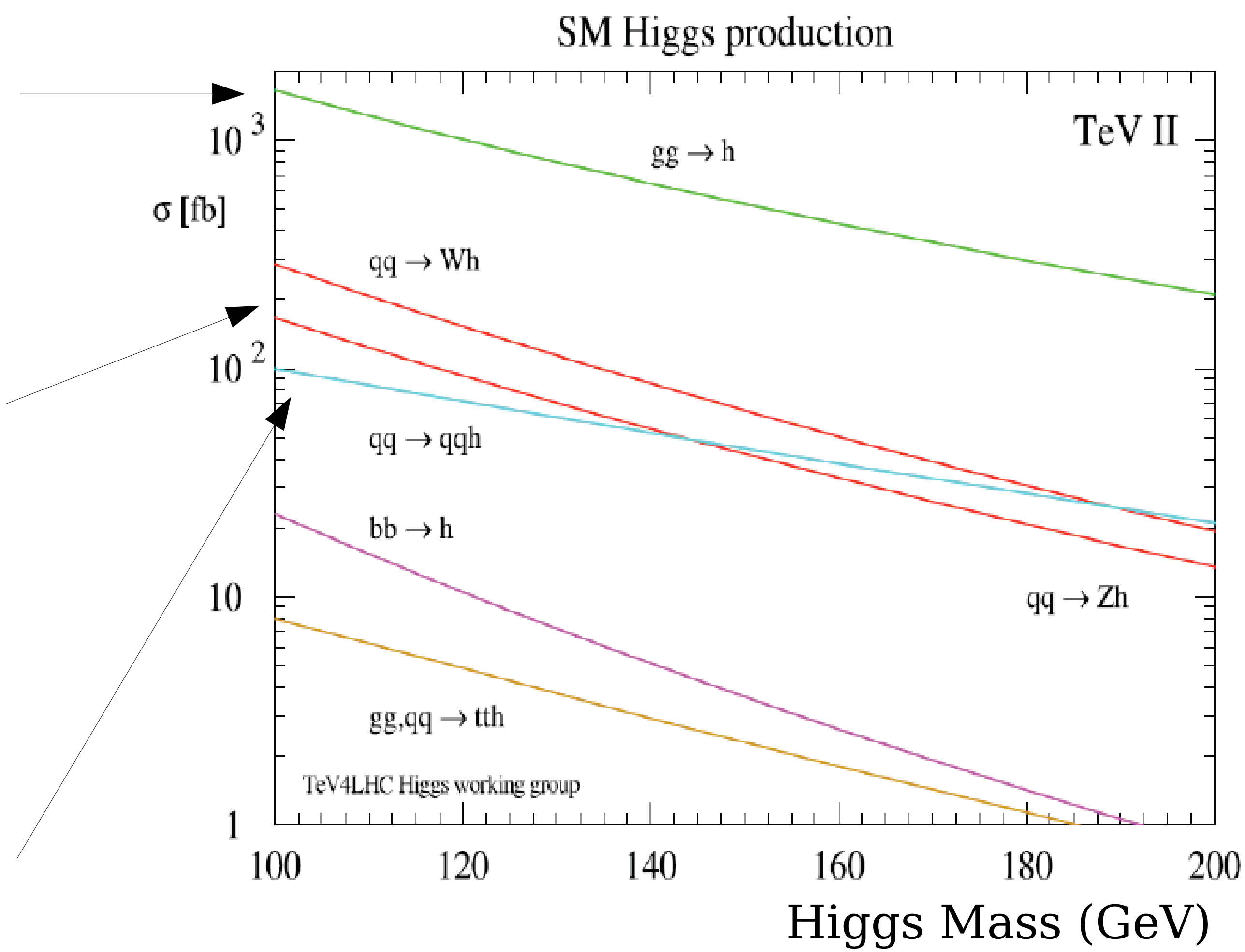


Electrons / photons
Muons
Jets / b-jets / taus
ME_T

Collaboration of ~550 physicists

SM Higgs Production at the Tevatron

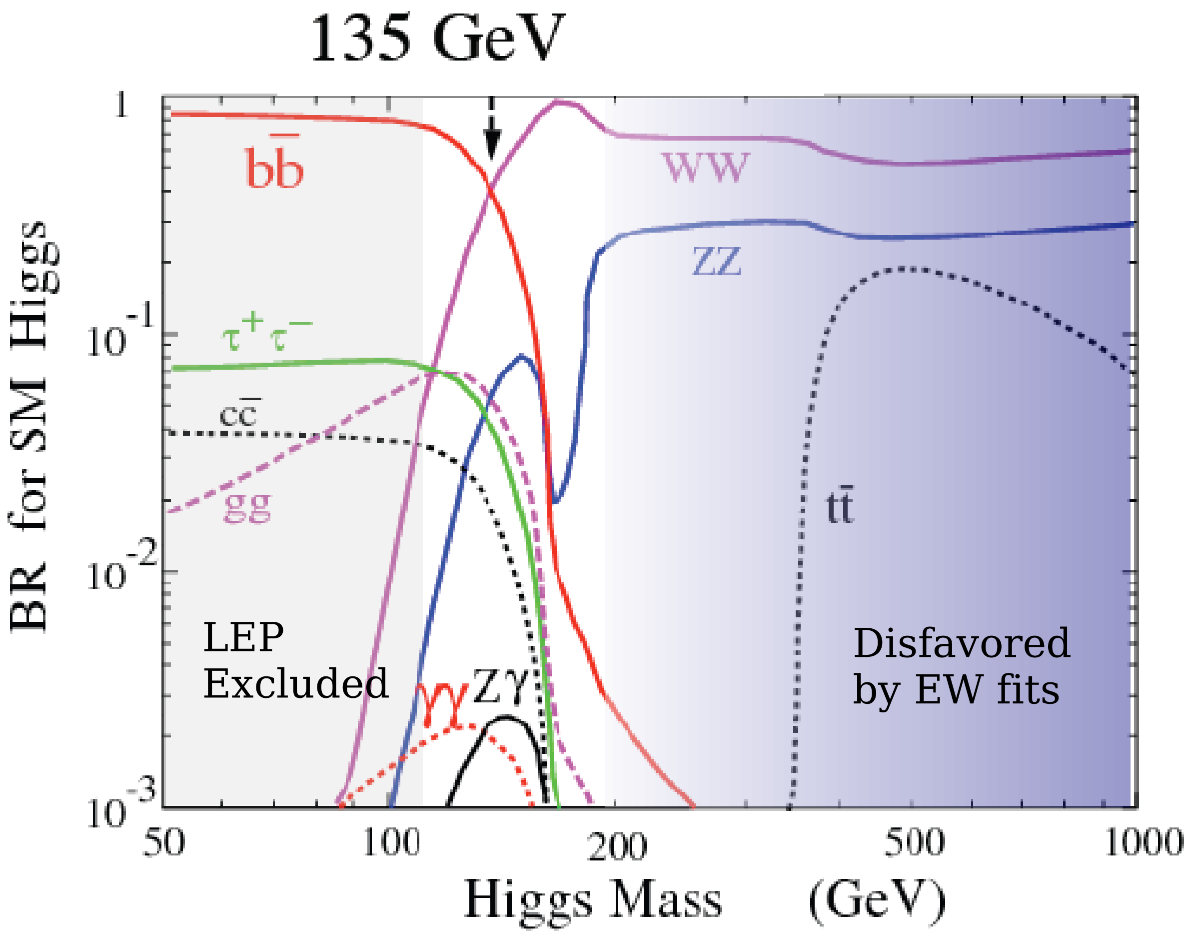




SM Higgs Decay

Low mass: **h→bb**

High mass: **h→WW**



Main SM Higgs Search Channels

	$H \to b\bar{b}$ (low mass)	$H \to WW$ (high mass)
$p\bar{p} \to H$	~~$H \to bb$~~	$H \to WW \to$ **lν lν**
$p\bar{p} \to WH$	$WH \to Wbb \to$ **lν bb**	$W/Z+H \to W/Z+WW \to$ $l^+l^-l^+ / l^+l^+jj + \nu$'s
$p\bar{p} \to ZH$	$ZH \to Zbb \to$ **ll bb** / **νν bb**	

b-jet Tagging

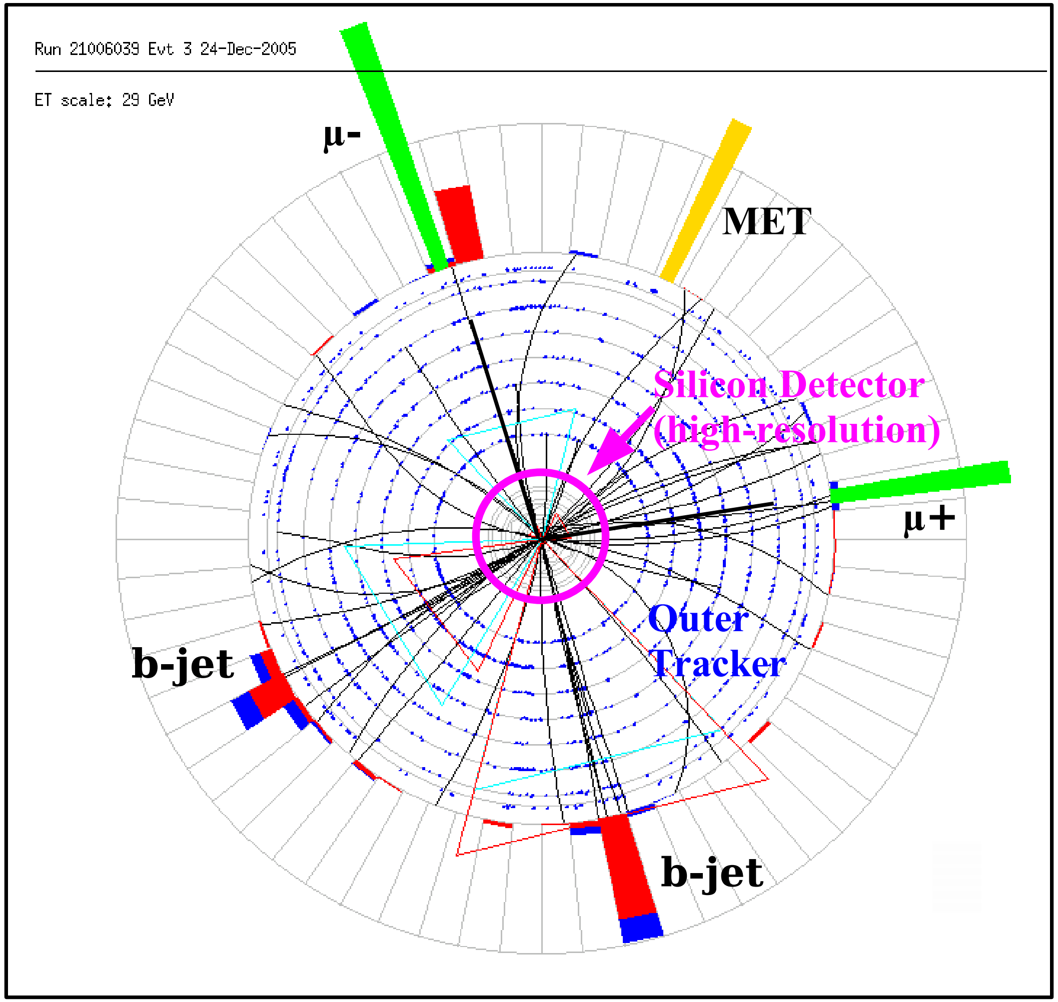
Low mass: **h→bb**

Identify jets with b's !

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

B hadrons are "long"-lived

- $\gamma c\tau$ =~ 3mm
- Reconstruct tracks *with high-resolution silicon*

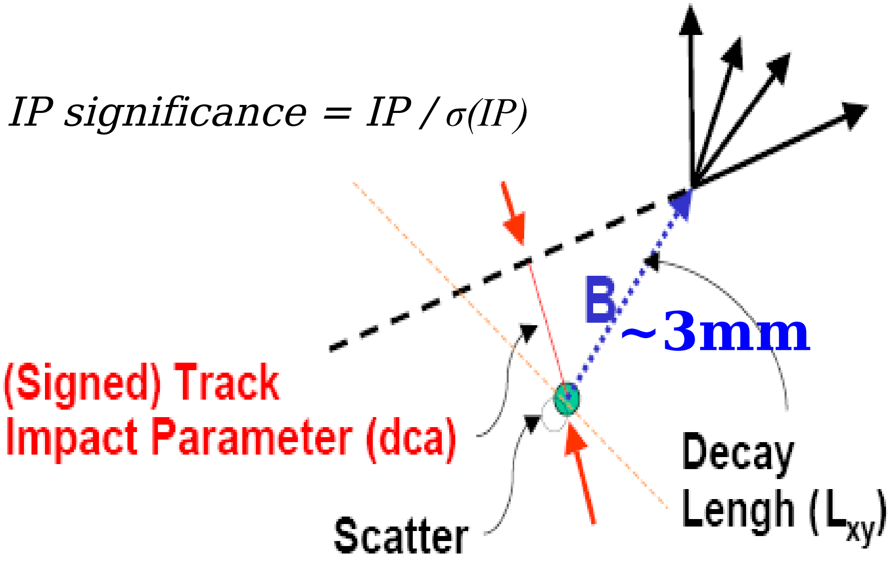


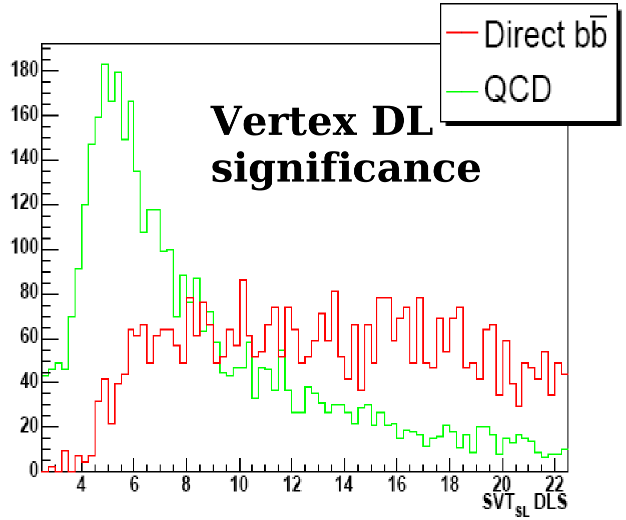
Simulated ZH→μμbb event

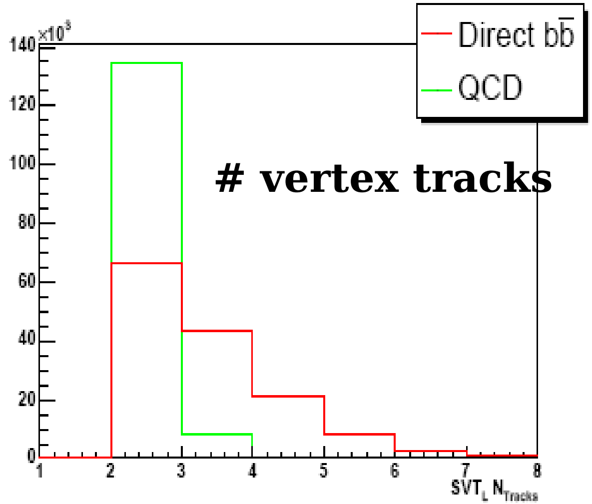
b-jet Tagging

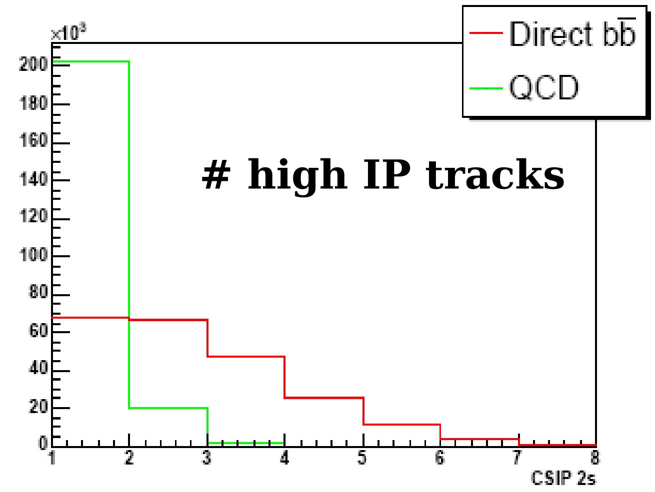
Many variables with separation:

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









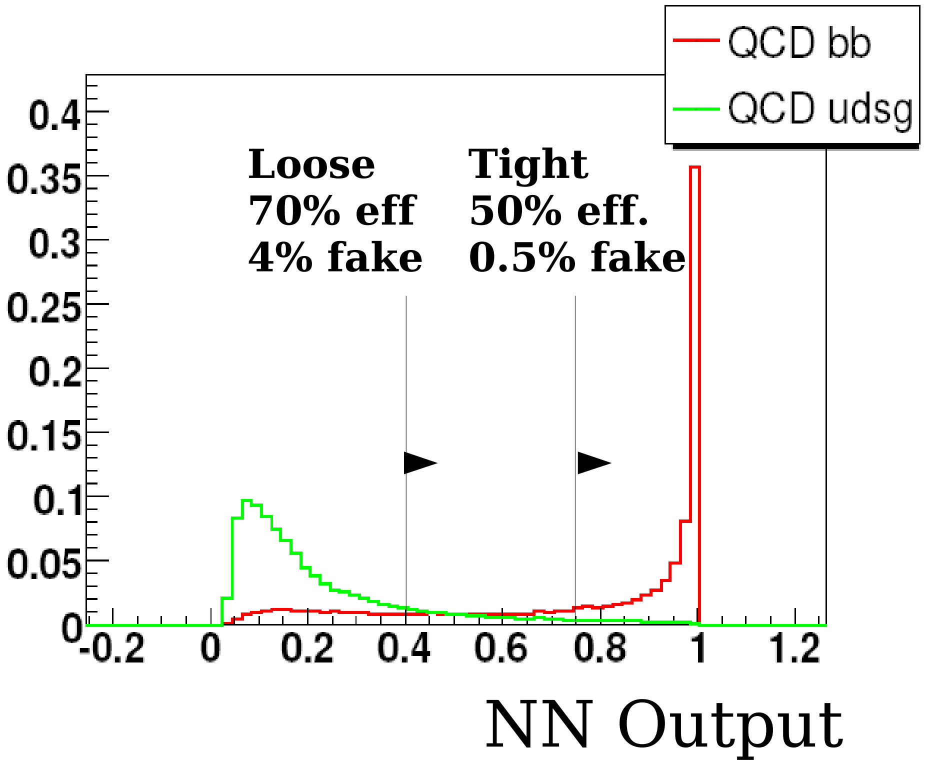
• • •

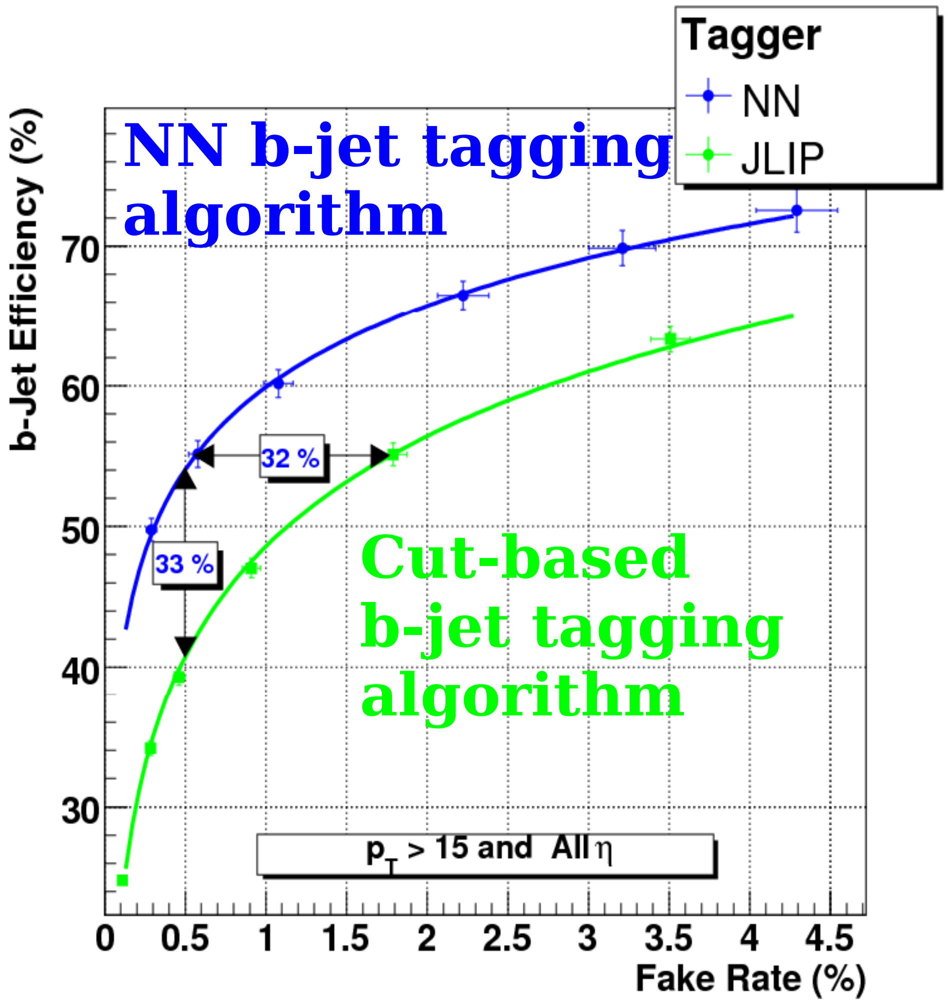
b-jet Tagging

Train artificial Neural Network on simulated events

- optimized inputs, training method, network topology

Test NN efficiency and fake rate using *real data*

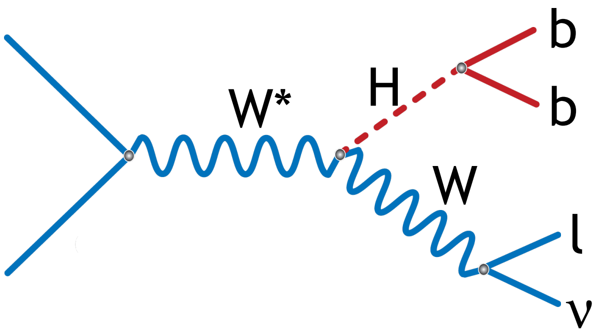




Equivalent to 2.5x as much data for a double-b-tag analysis!

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

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



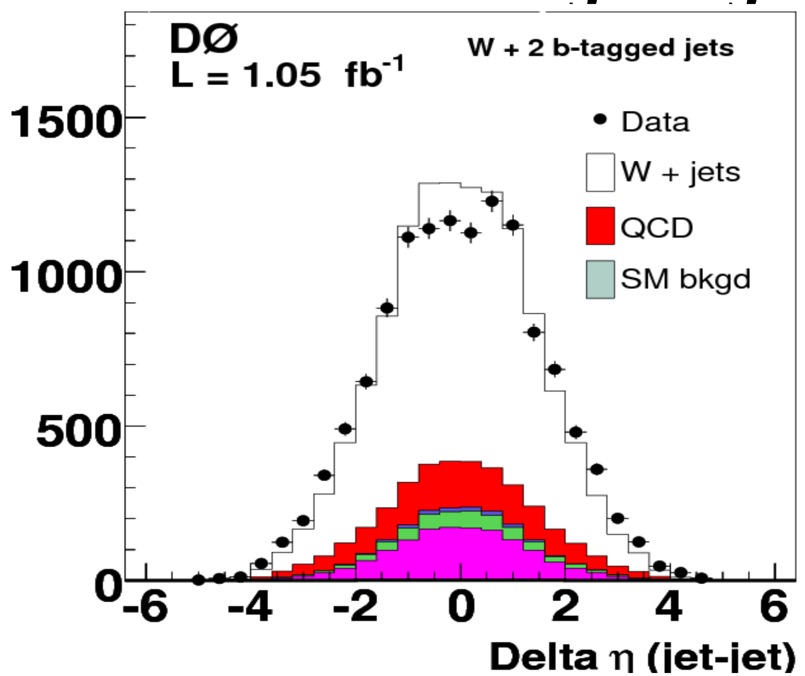
QCD: jets which fake leptons

- Measured from data in low ME_T events

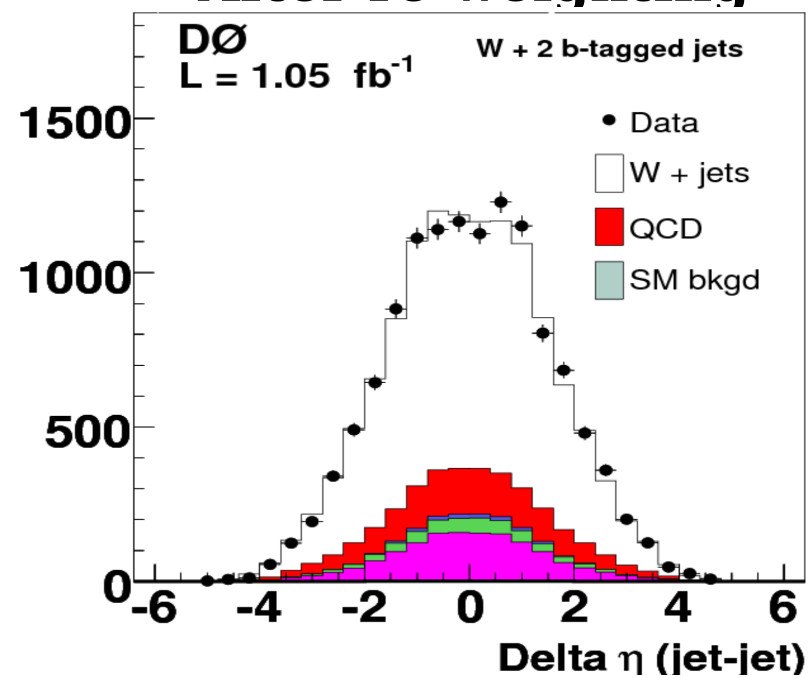
ALPGEN MC used to model W+jets

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

Before re-weighting



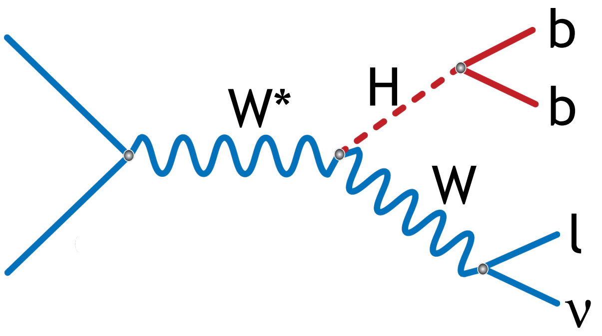
After re-weighting



Also $\Delta\varphi$

WH→ (e/μ)ν bb

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



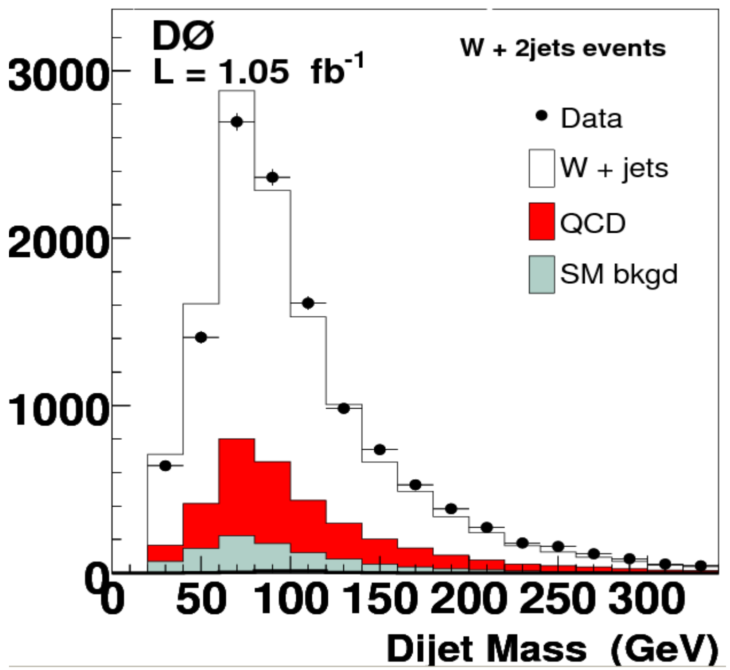
QCD: jets which fake leptons

- Measured from data in low ME_T events

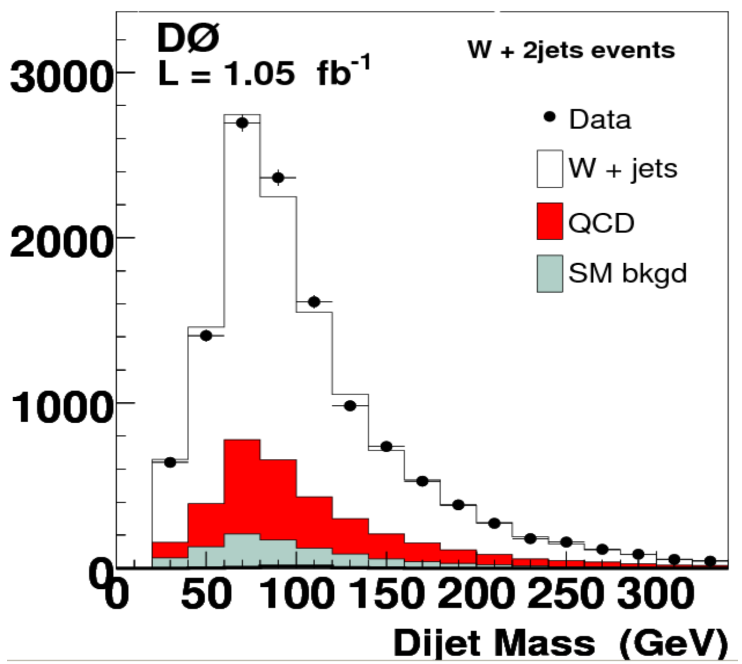
ALPGEN MC used to model W+jets

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

Before re-weighting



After re-weighting



Improved dijet mass modeling

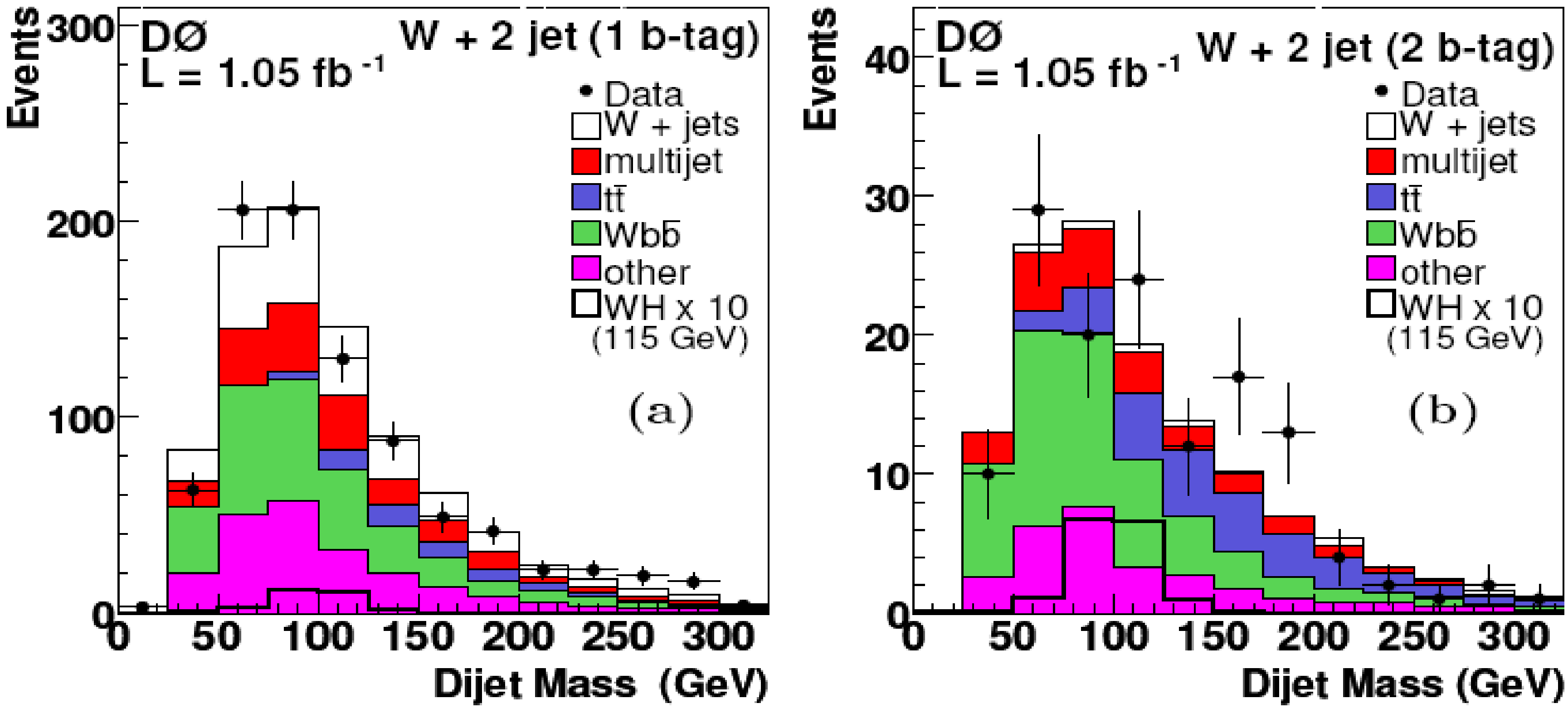
WH→ (e/μ)ν bb

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→ (e/μ)ν bb

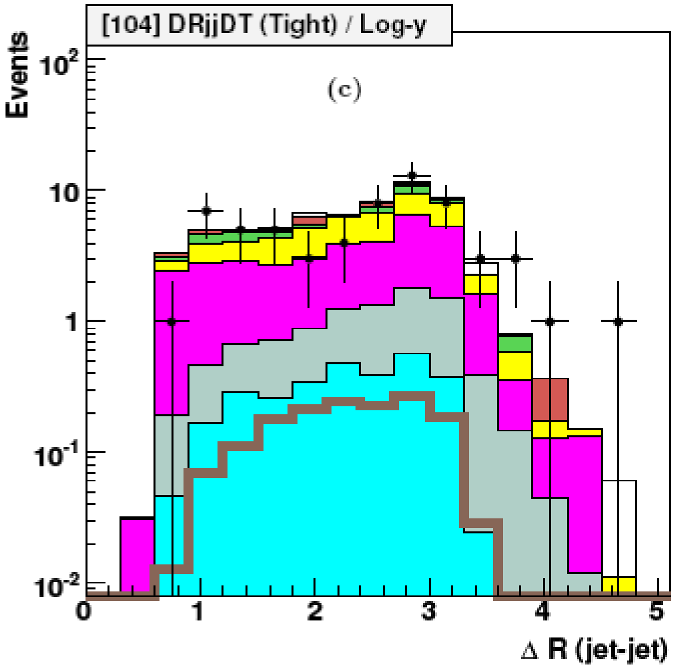
Artificial Neural Network used to increase S/B using more variables

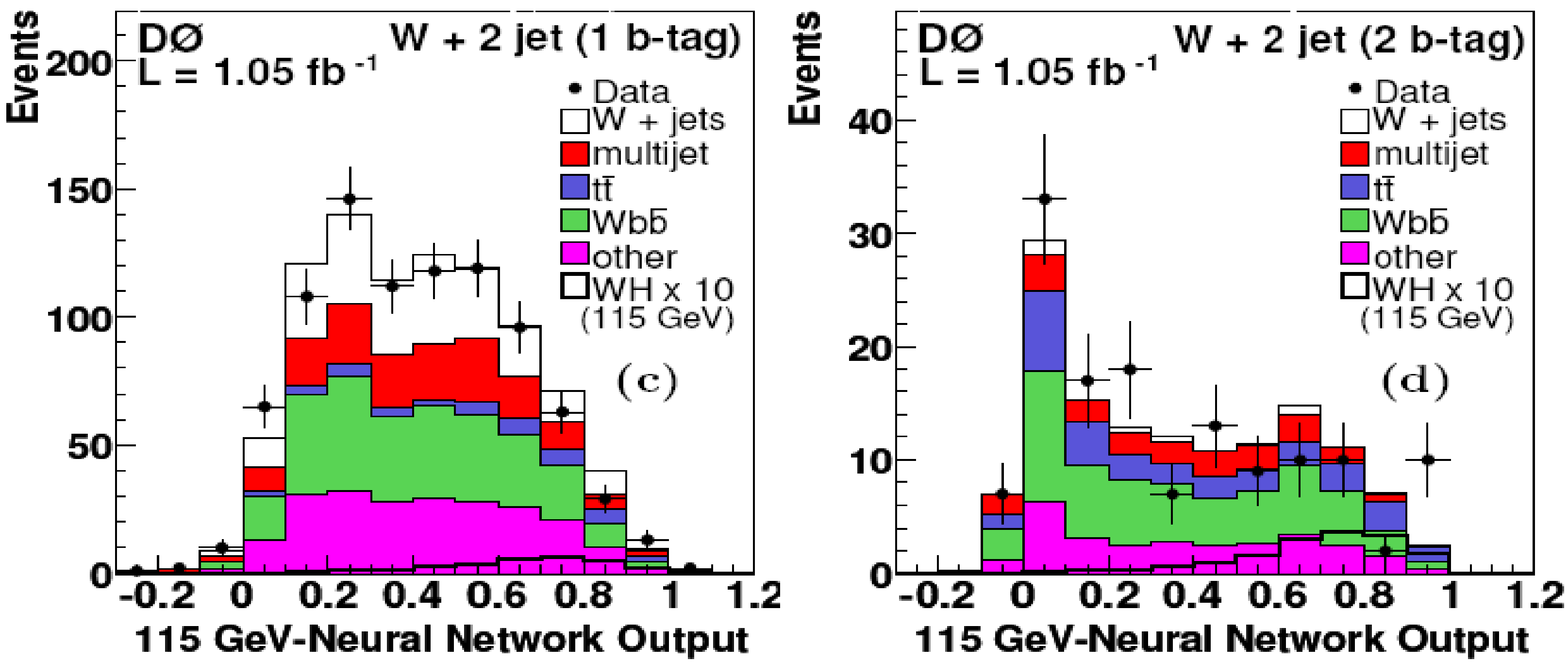
Dijet mass

Angle between jets

Jet, lepton energies

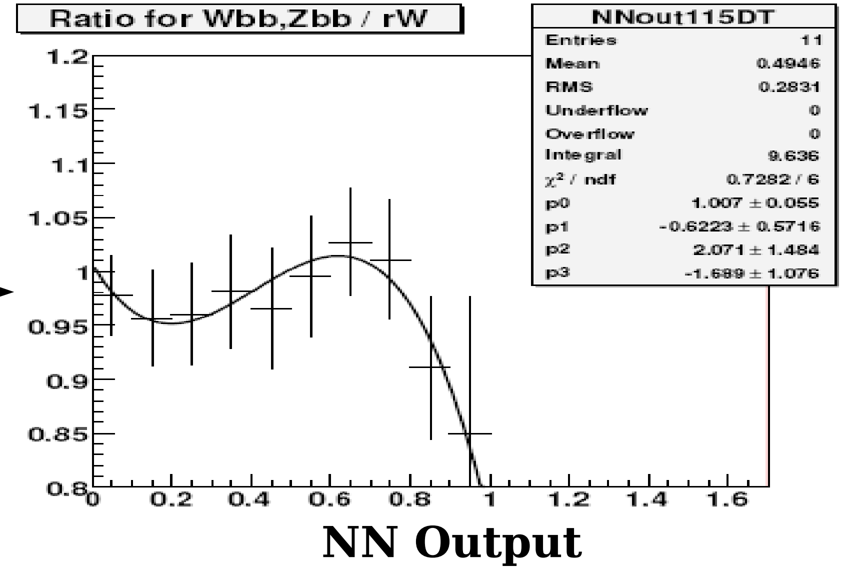
W transverse momentum





WH→ (e/μ)ν bb

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

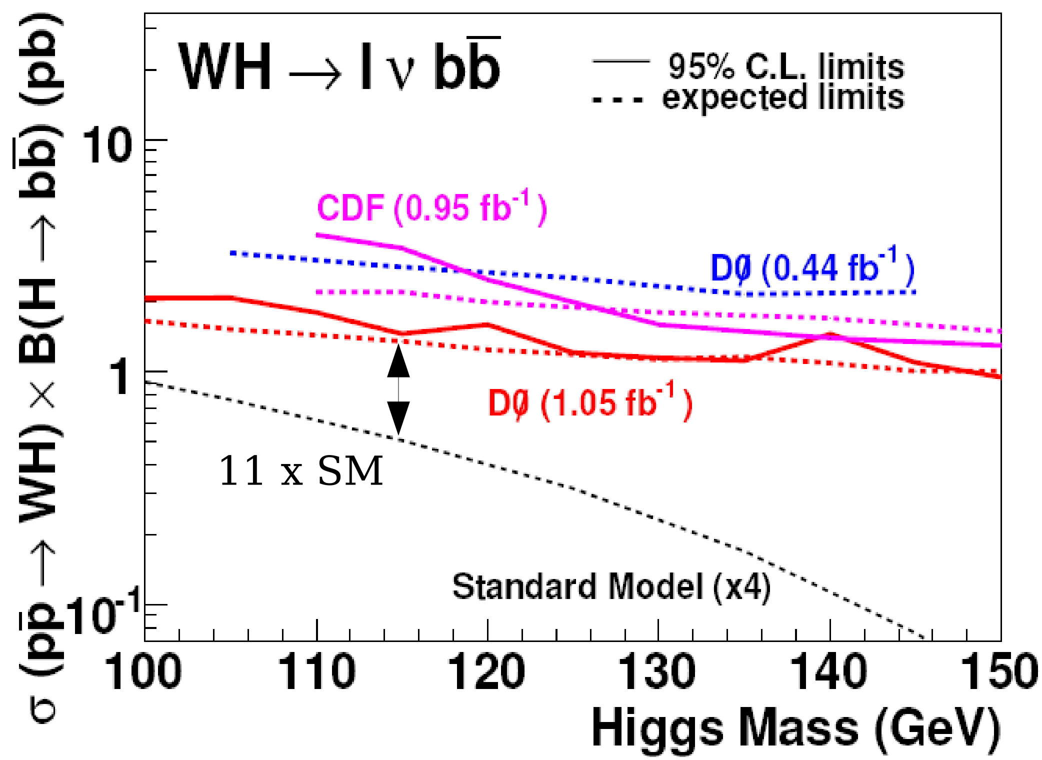


Also take advantage of better acceptance
~2x more sensitive than cut-based analysis

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

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

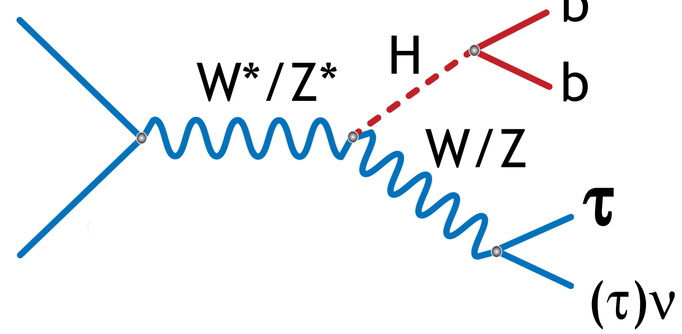
Soon extend larger 3/fb data set



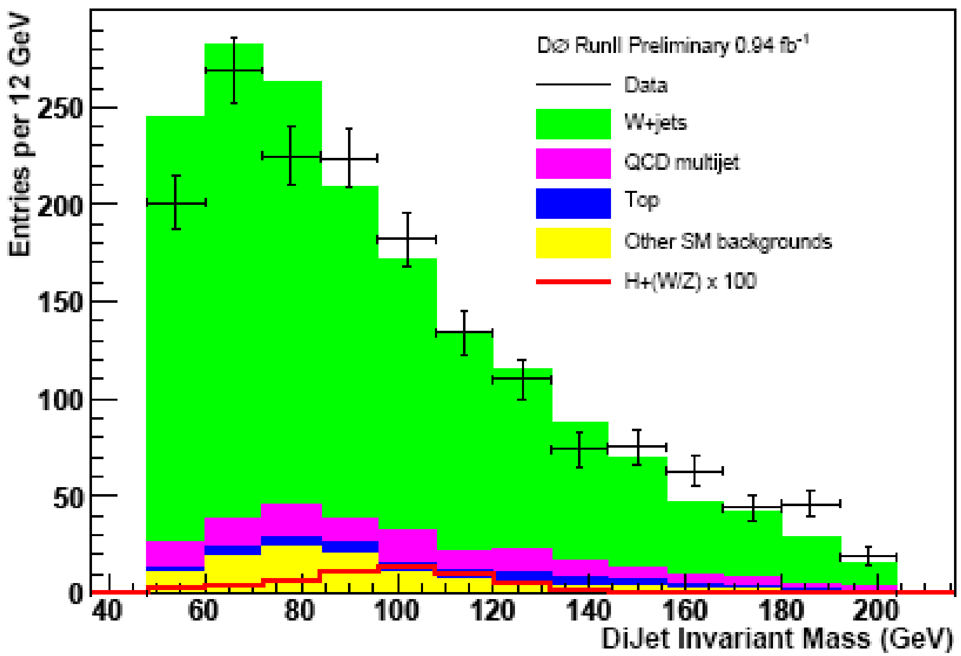
WH→ τν bb

New channel!
1/fb only, trigger on jets + ME_T

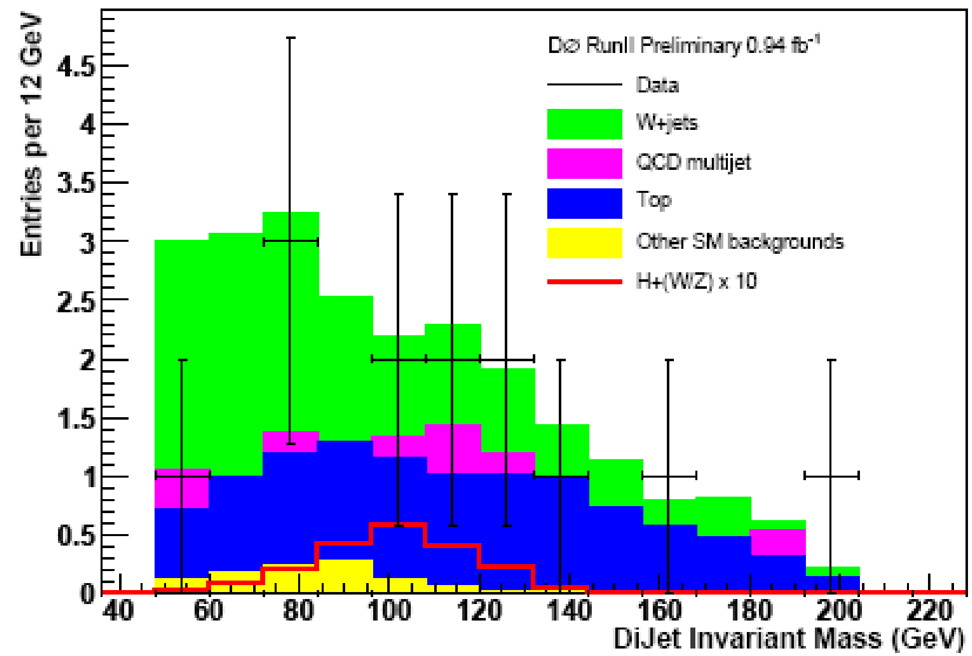
Limit ~ 35x SM @115 GeV



Before b-tagging



After b-tagging

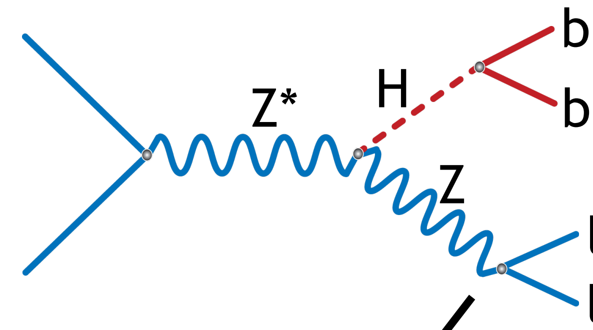


ZH→ ll bb

Very clean signature!

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

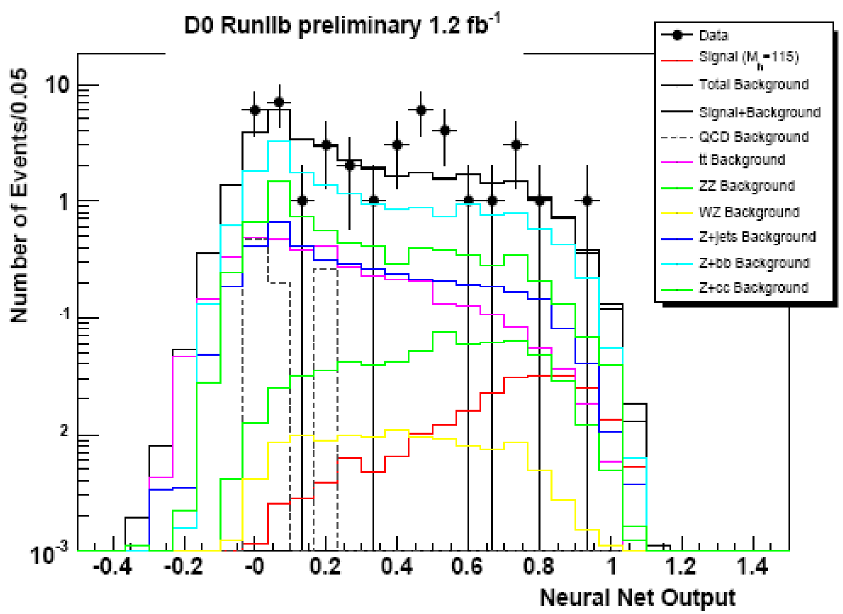
- OR of single and double lepton triggers ~100% efficient

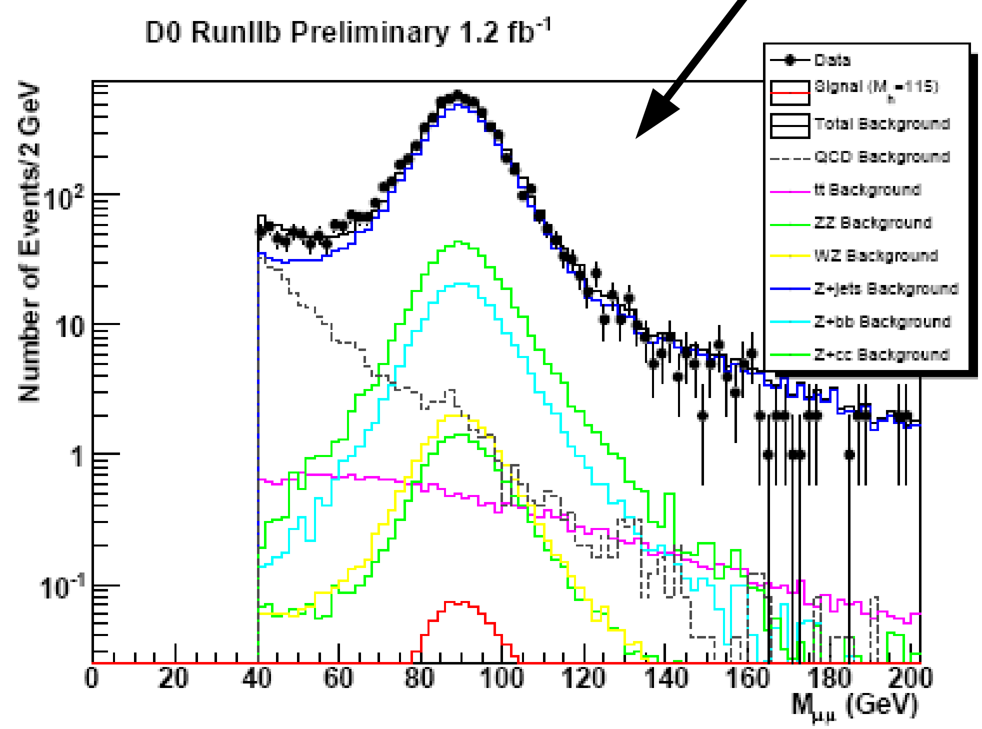


Recently updated analyses to 2.3/fb

Neural Network used (ME underway)

Limit ~ 12x SM @115 GeV





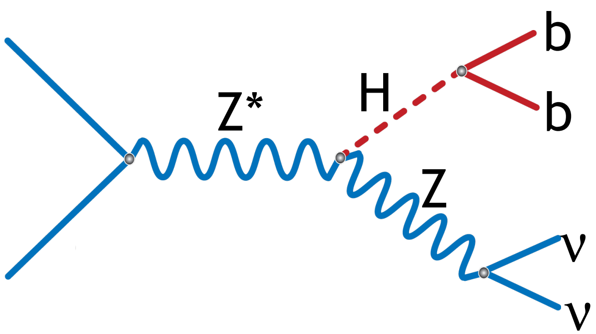
ZH→ νν bb

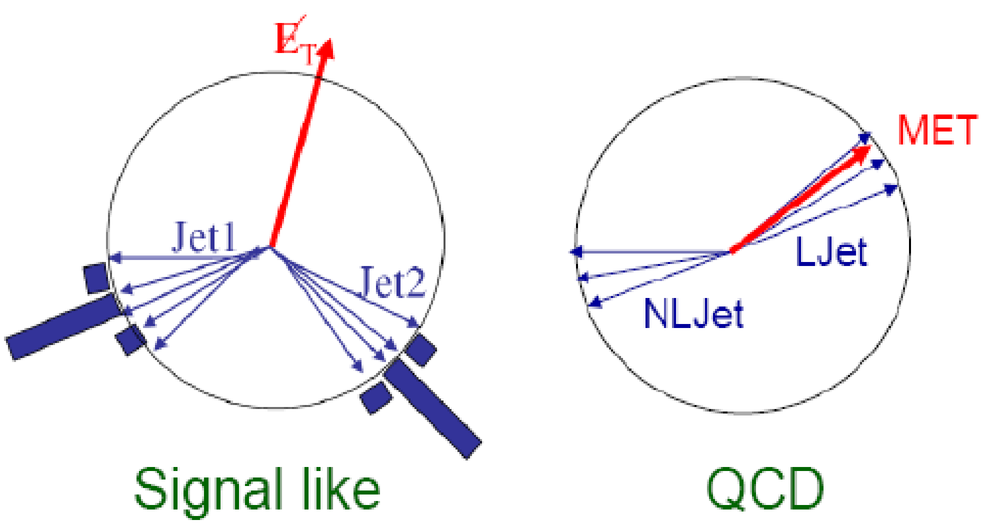
2.1/fb analyzed, triggered on jets and ME_T

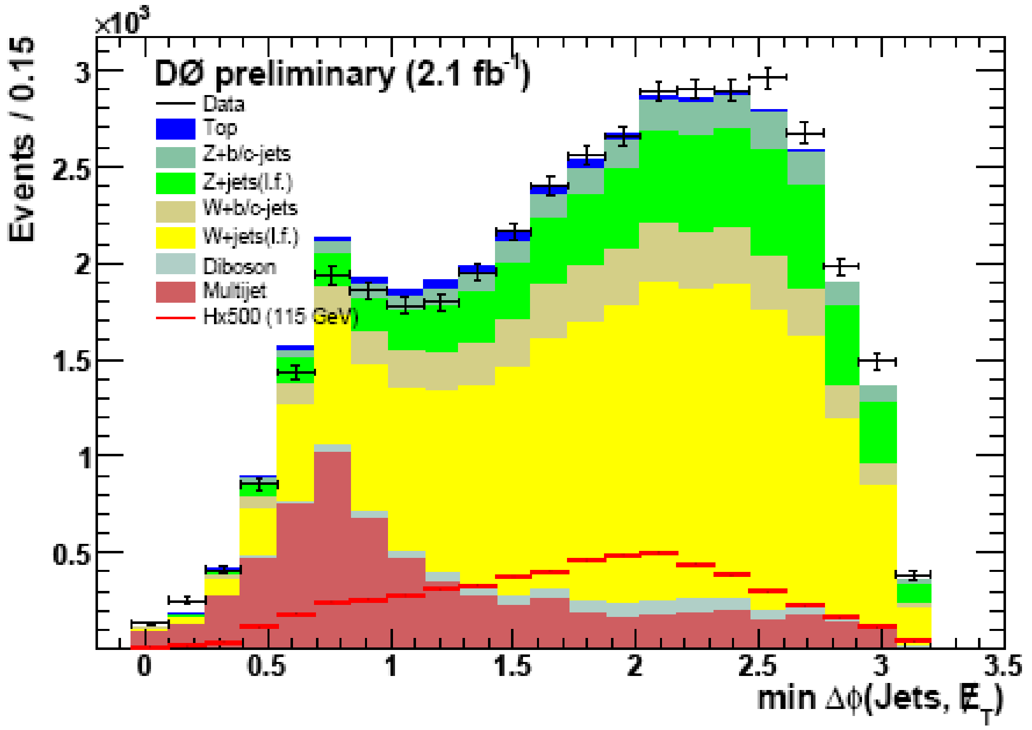
Also include WH signal when lepton is lost

QCD estimated from data

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





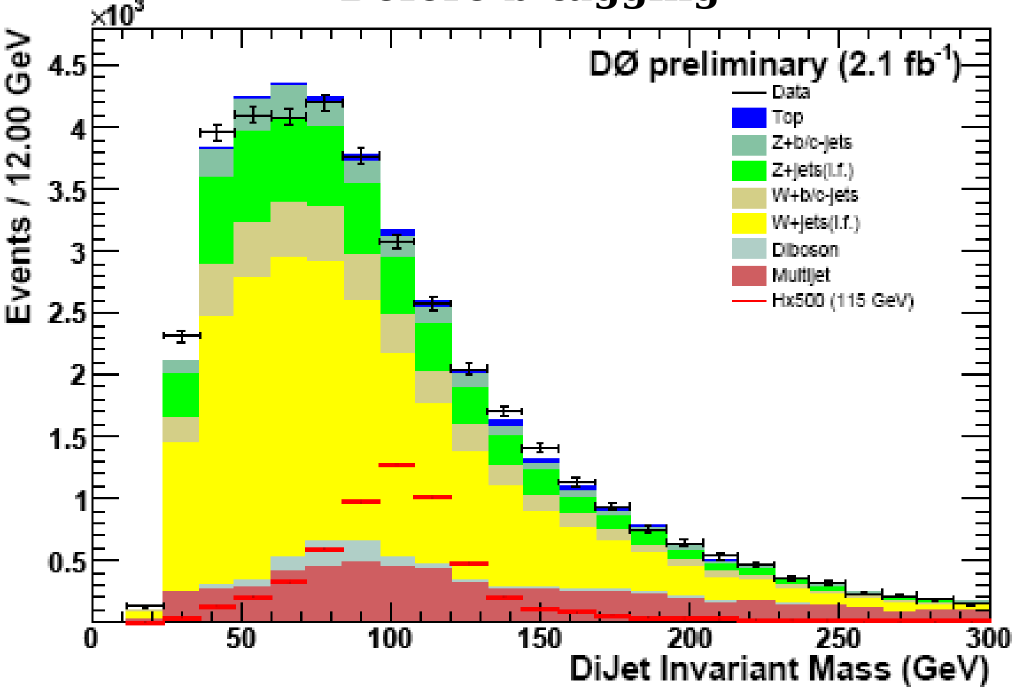


ZH→ νν bb

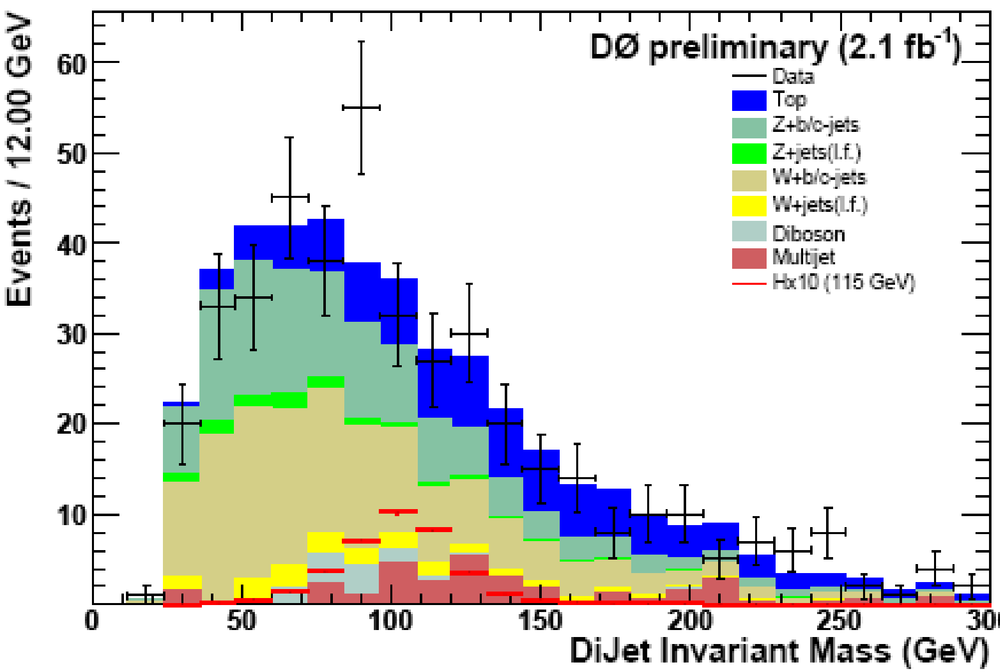
Checks performed before b-tagging

Look for signal after b-tagging

Before b-tagging



After (double) b-tagging

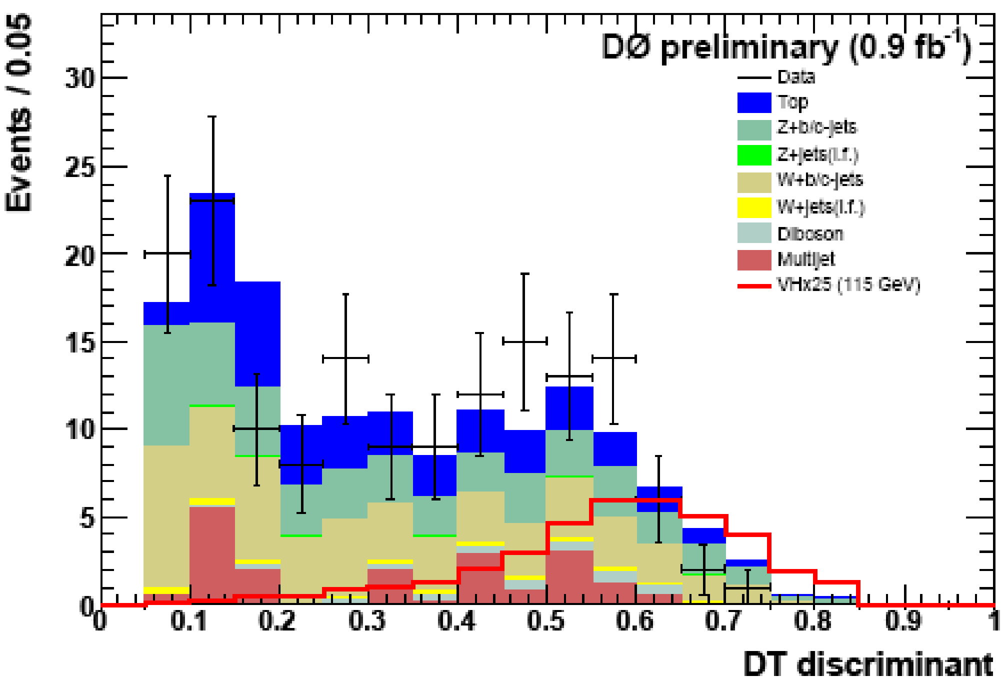


ZH→ νν bb

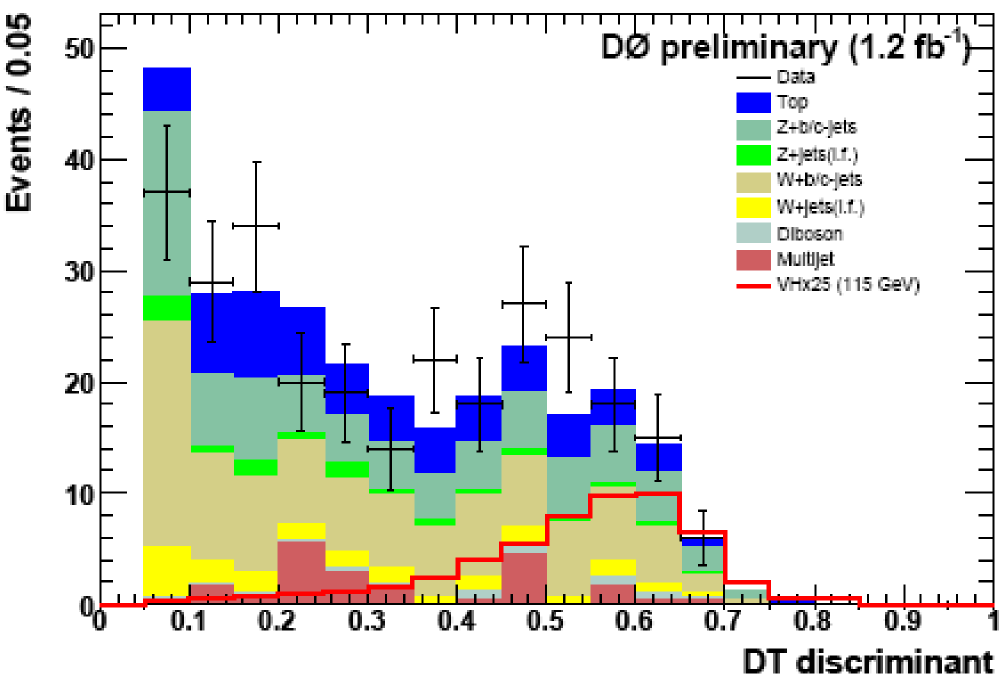
Use Boosted Decision Tree to separate signal from background

Limit ~8x SM @115 GeV

Run IIa



Run IIb (analyzed so far)



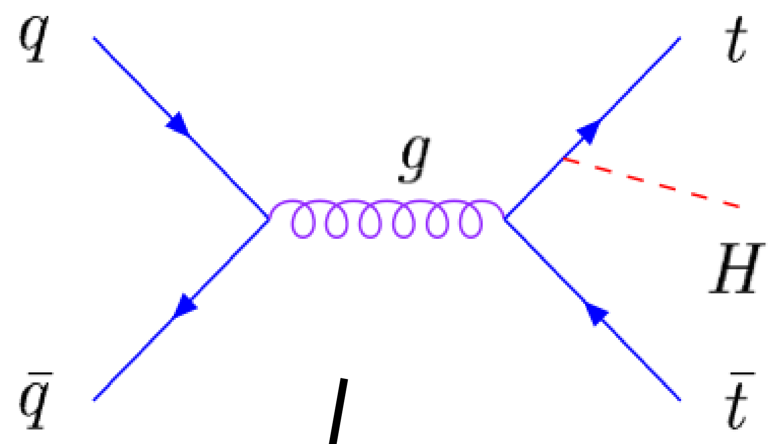
tth→ tt bb

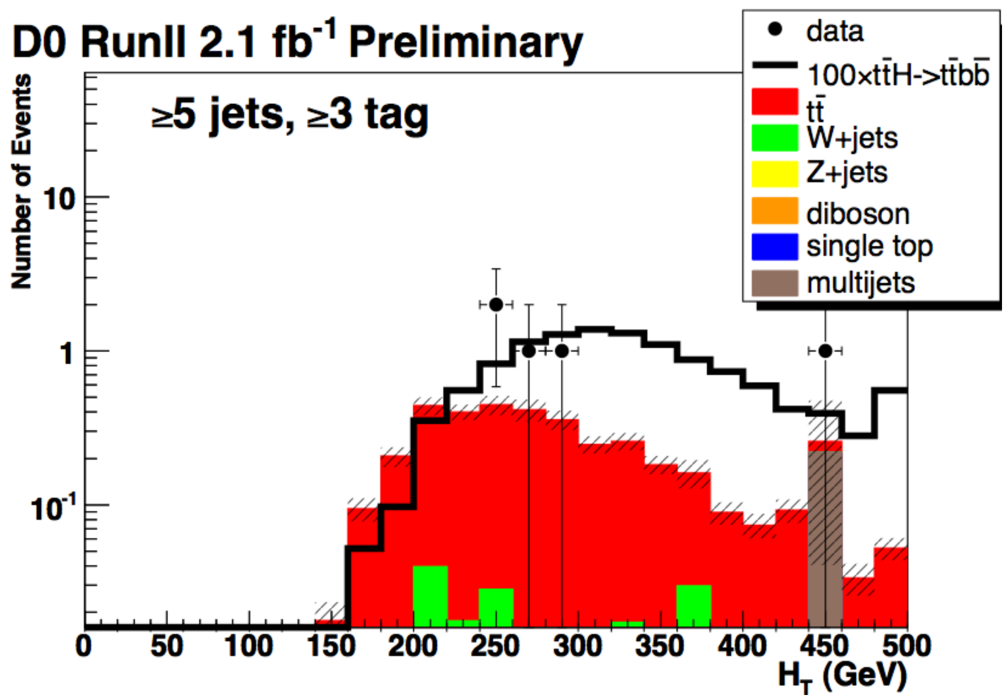
New channel!

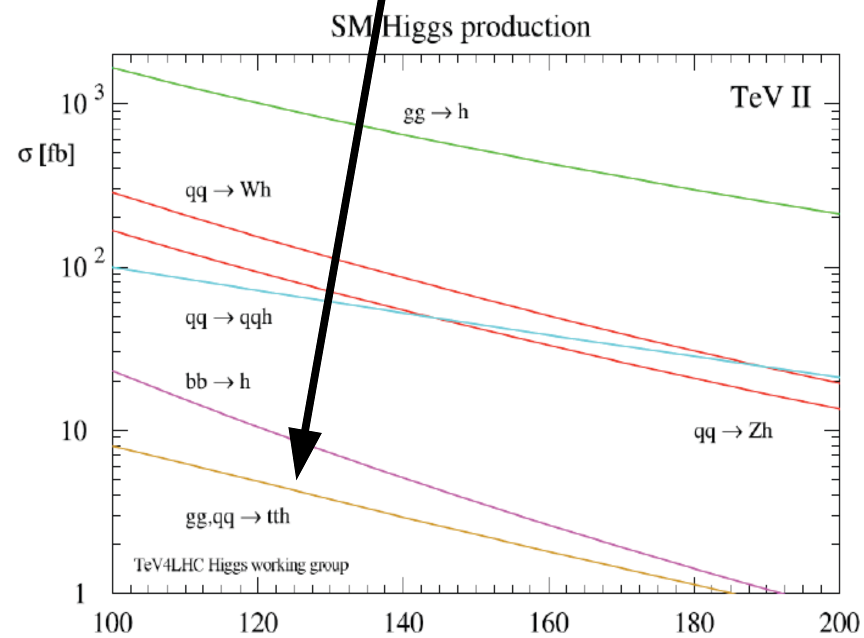
Tiny cross-section, but relatively clean

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

Limit ~ 45x SM @115 GeV







h→ γγ

Tiny cross-section, but relatively clean
- Can be enhanced by new physics (fermio-phobic)

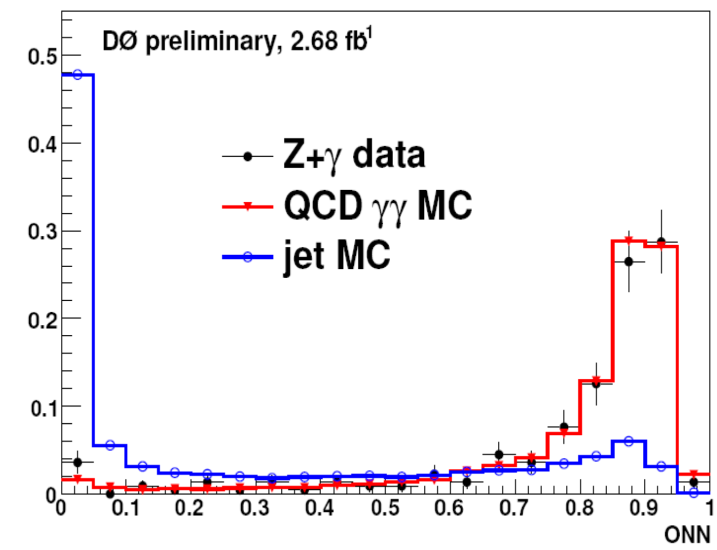
Advanced photon-ID Neural Network

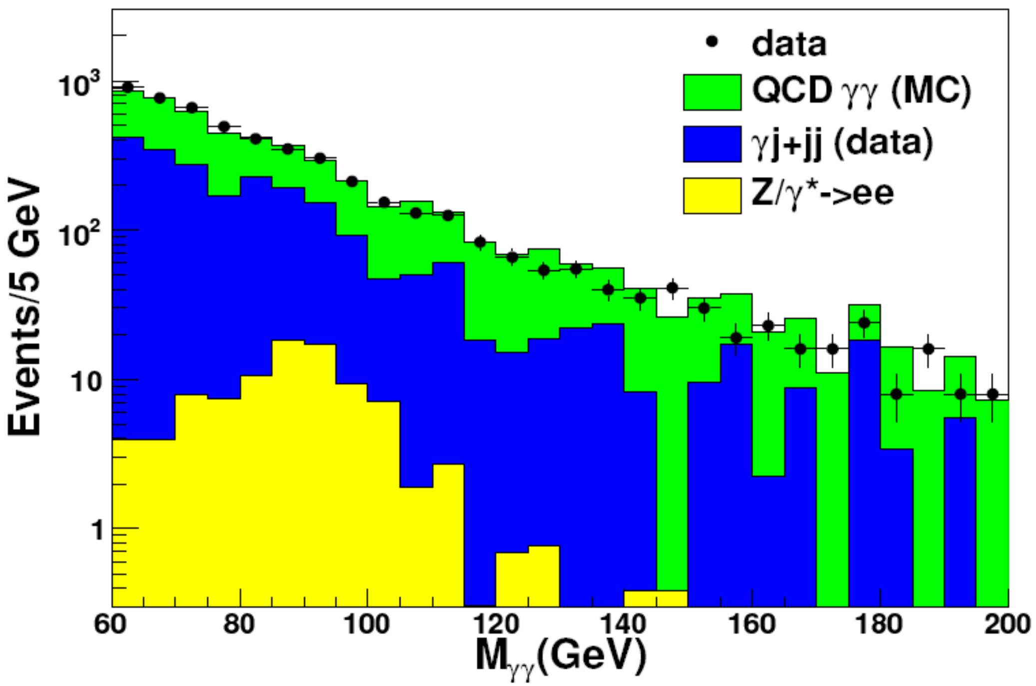
Di-jet and γ+jet measured in data

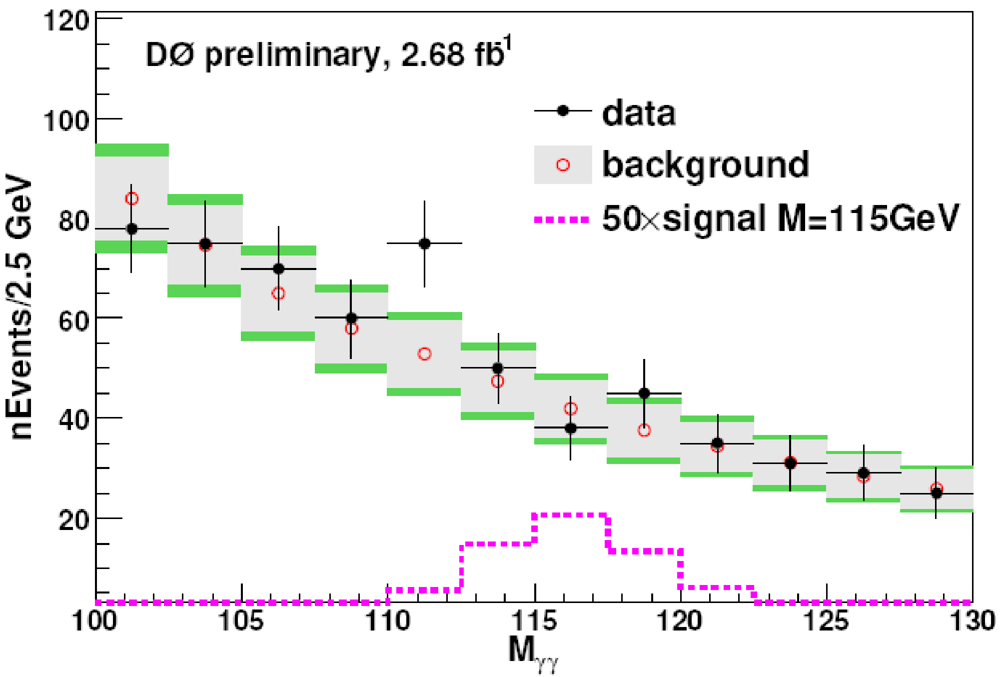
Data agrees with Pythia re-weighted to DIPHOX

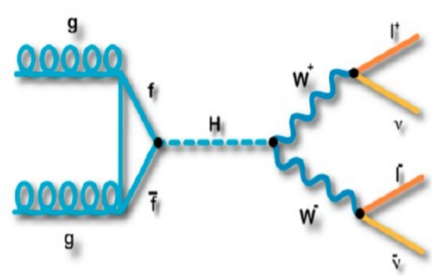
Important channel for LHC, tested at DØ

Limit ~ 23x SM @115 GeV









H→WW→ lν lν

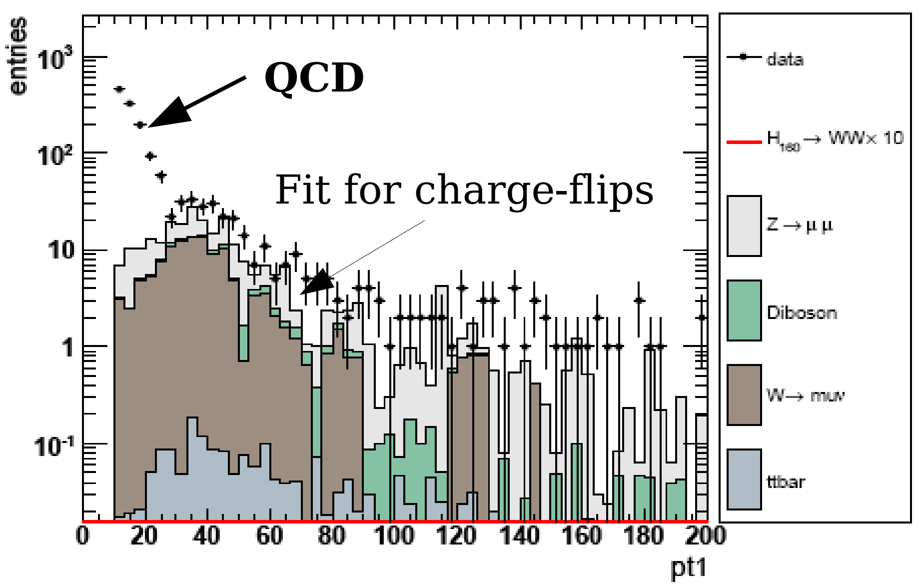
3.0/fb

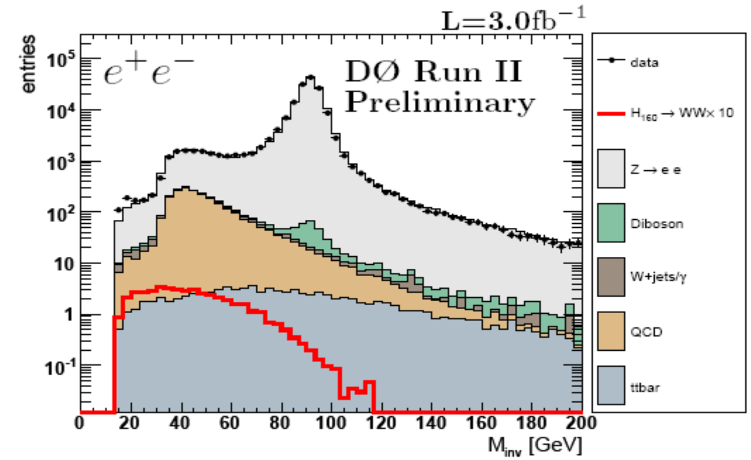
Dominates sensitivity for m_H>~135 GeV

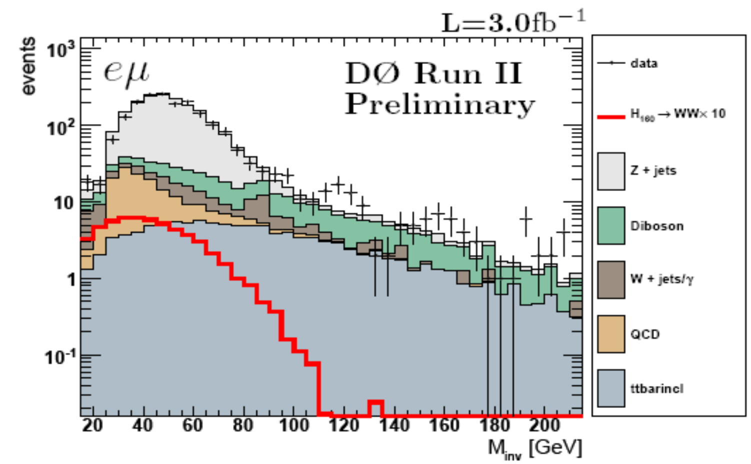
Select di-lepton events (~100% trigger eff.)

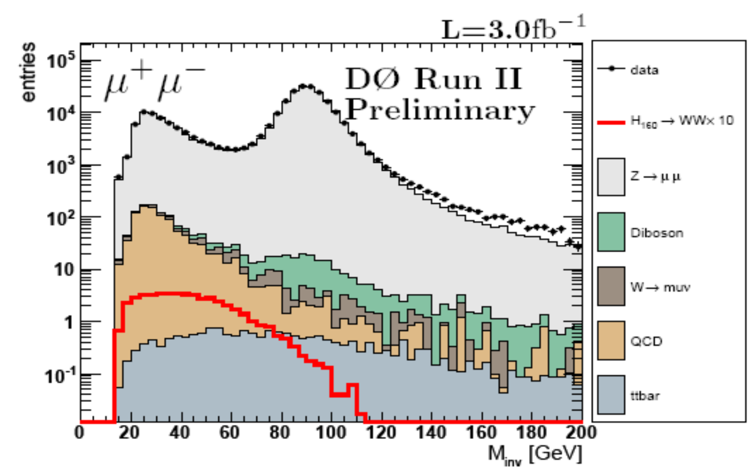
Study and compare to Z→ee, μμ, ττ(→eμ)

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





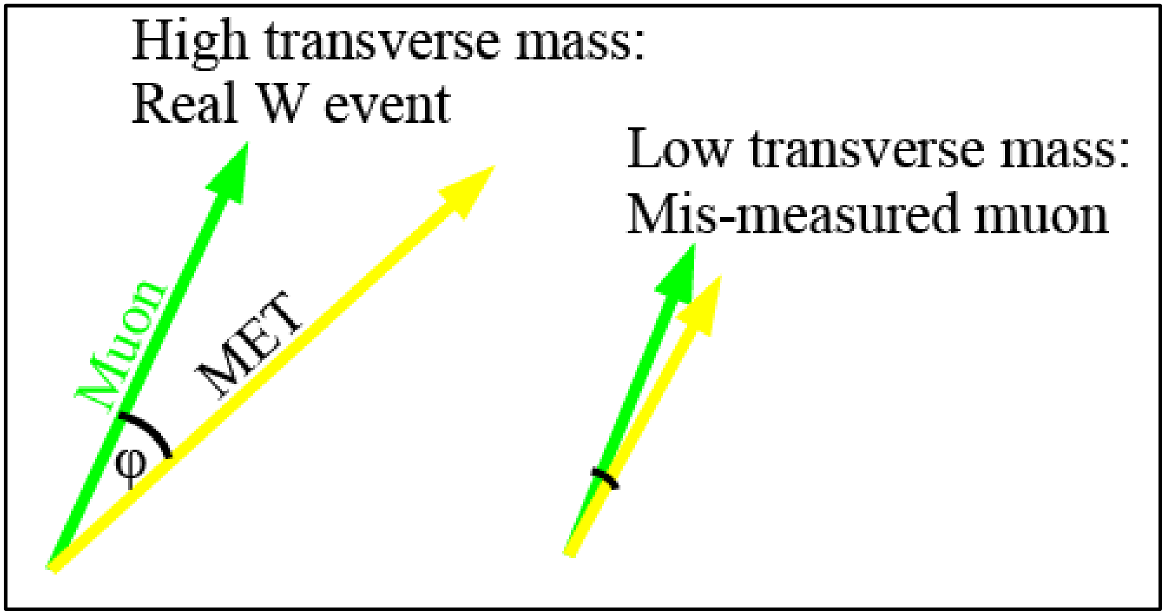


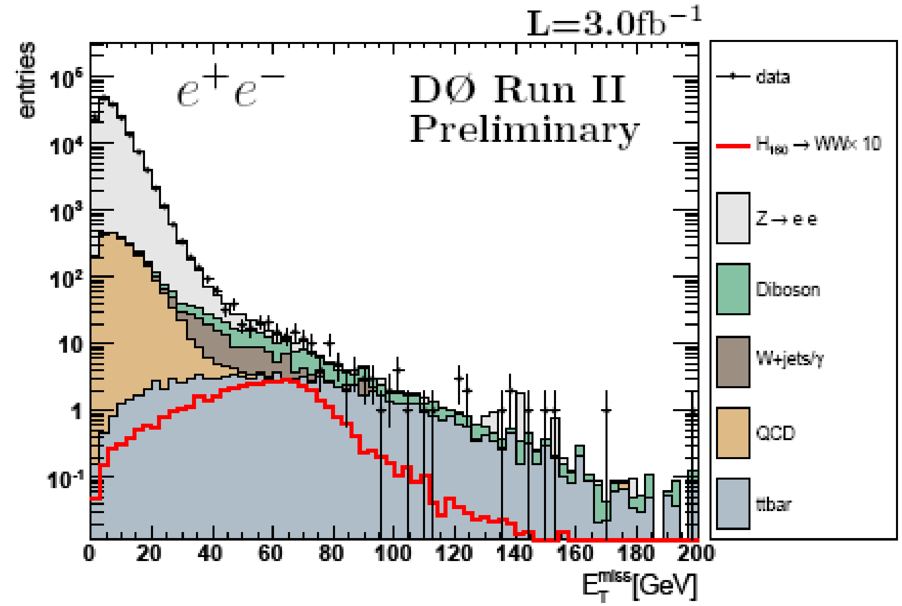


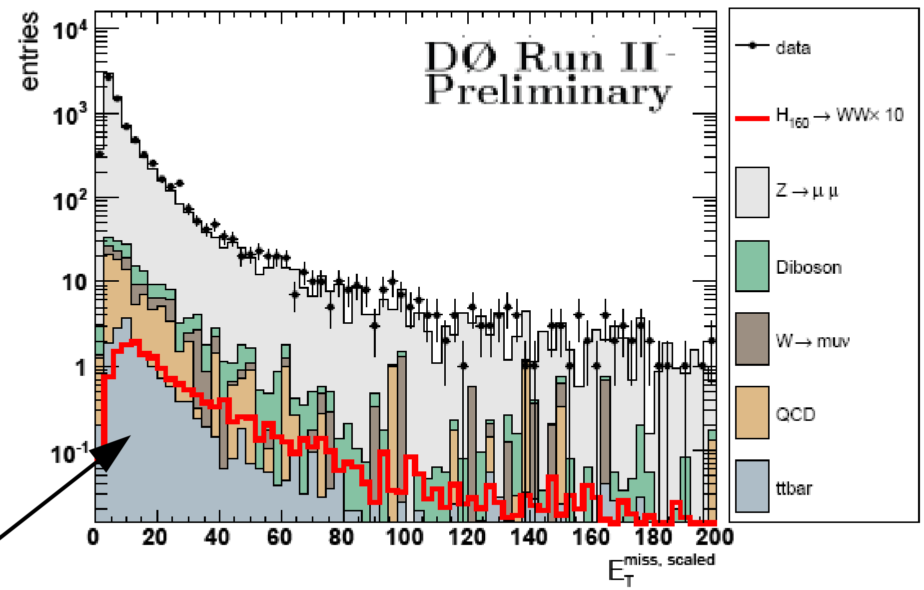
H→WW→ lν lν

Signal has large ME_T and ME_T *significance*

ME_T is not aligned with either lepton







$$\not{E}_T^{\text{Scaled}} = \frac{\not{E}_{\text{T}}}{\sqrt{\sum_{\text{jets}} \left(\Delta E^{\text{jet}} \cdot \sin\theta^{\text{jet}} \cdot \cos\Delta\phi\left(\text{jet}, \not{E}_{\text{T}}\right)\right)^2}}$$

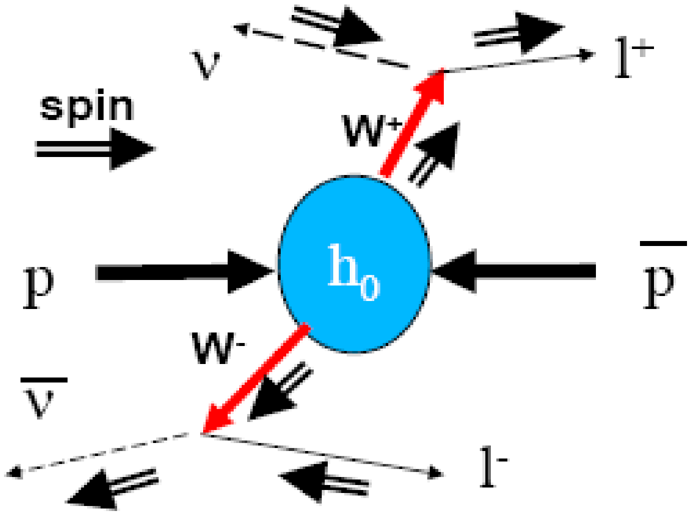
MET projected onto jet direction

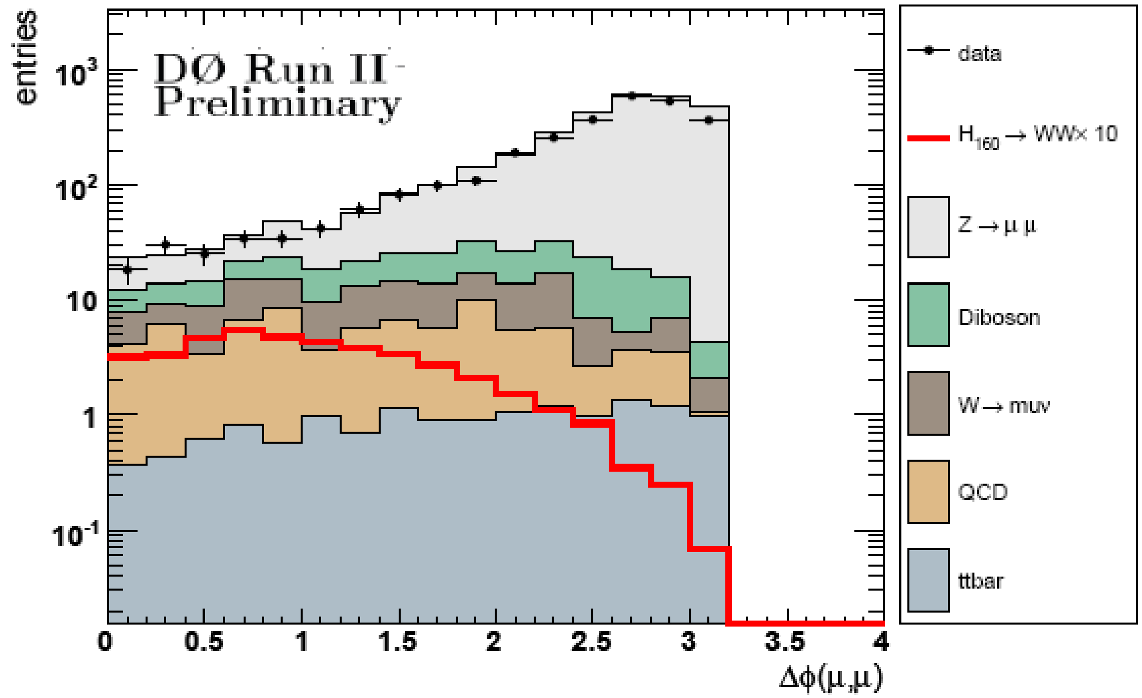
H→WW→ lν lν

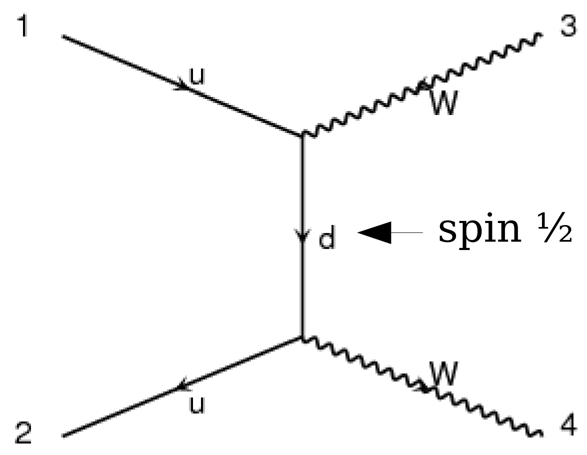
**Higgs is a scalar,
leptons are more aligned**

qq→WW (spin ½ quark, spin 1 boson),
leptons are less aligned

Z→ll is also back-to-back, not aligned







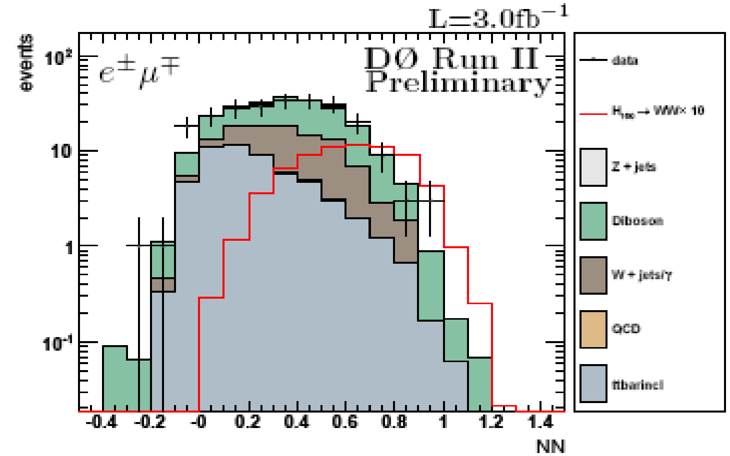
H→WW→ lν lν

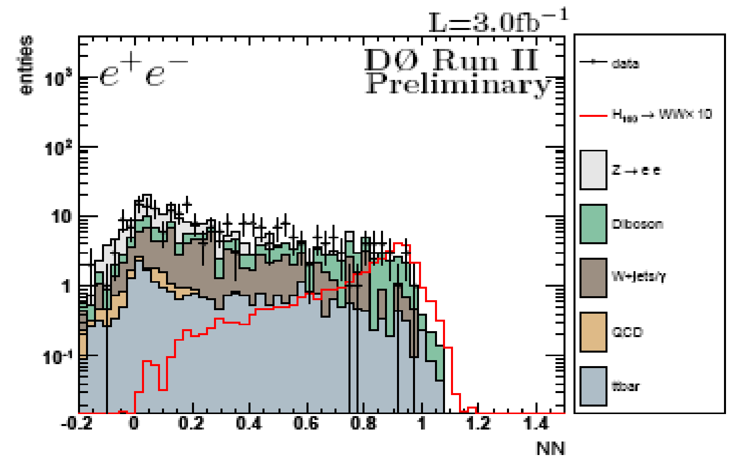
Artificial Neural Net used to separate signal

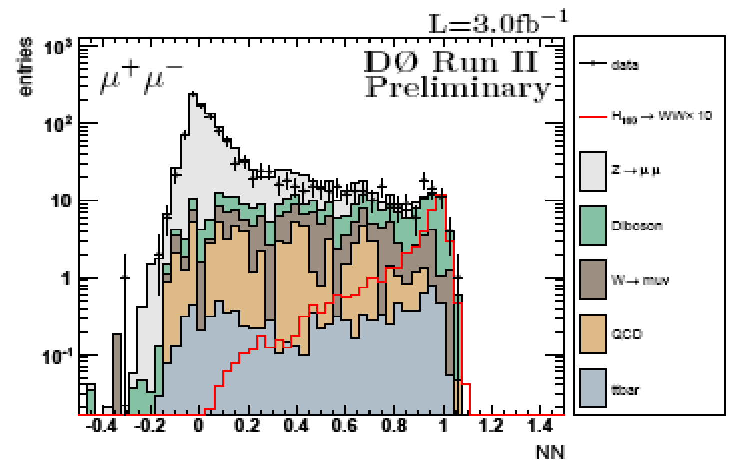
- Trained against weighted sum of all backgrounds
- Each lepton channel independently
- Each mass (every 5 GeV) independently

~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	$M_t^{min}(l,\not{E}_T)$	$\Delta\phi(\not{E}_T,l_1)$
Σ jet P_T (H_T)	$\not{E}_T$	$\Delta\phi(\not{E}_T,l_2)$
Lepton Quality	$\not{E}_t^{scalar}$	







H→WW→ lν lν

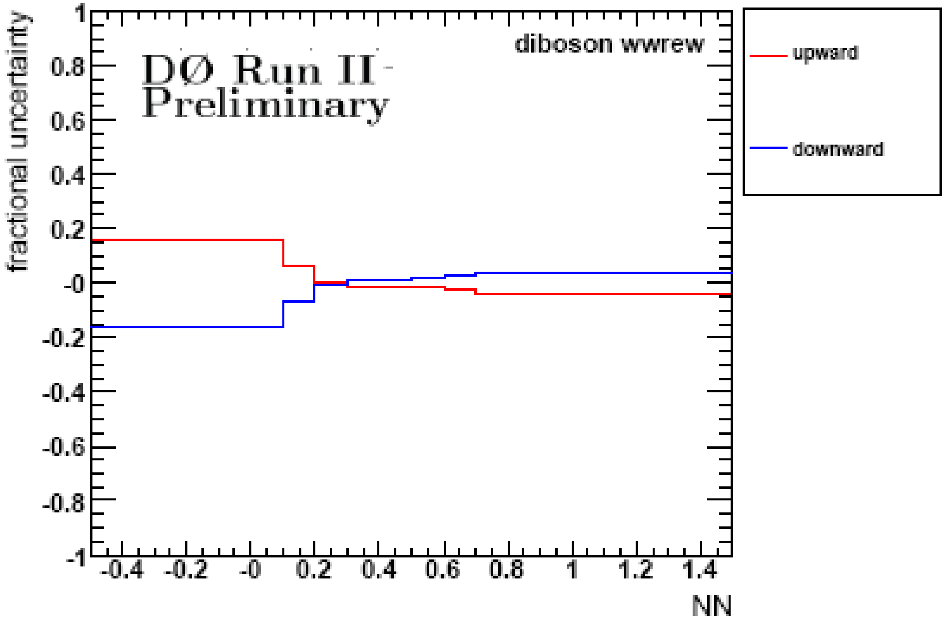
Flat systematics:

- Lepton efficiencies (2-8%)
- Lepton momentum scale (2%)
- Theoretical cross-sections (7-10%)
- Jet→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%)

Change in NN output when changing WW pT

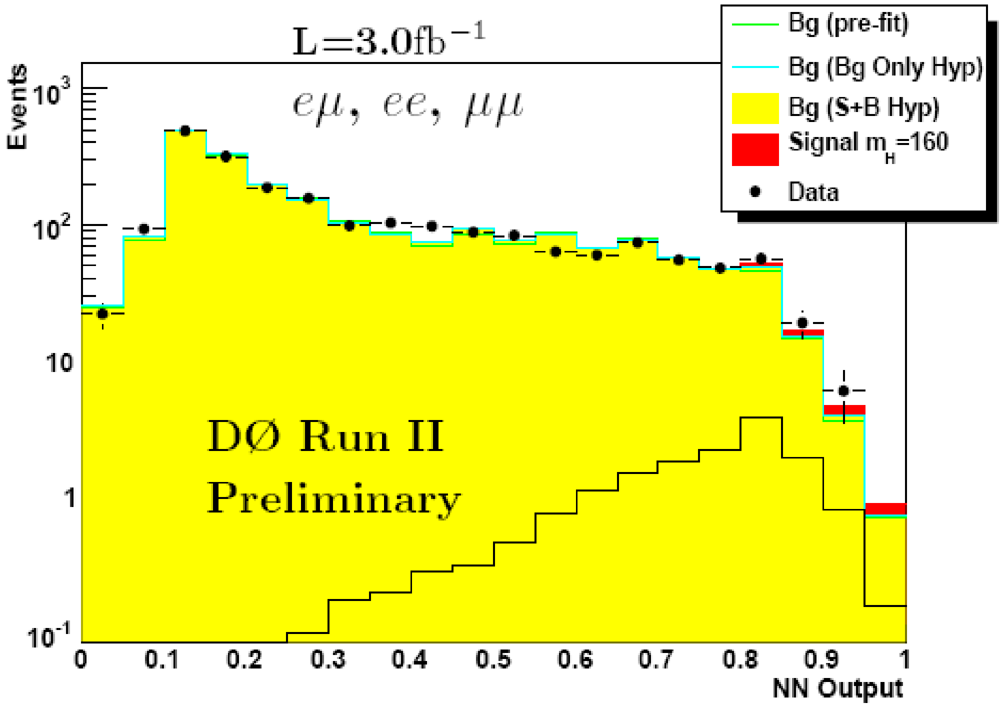


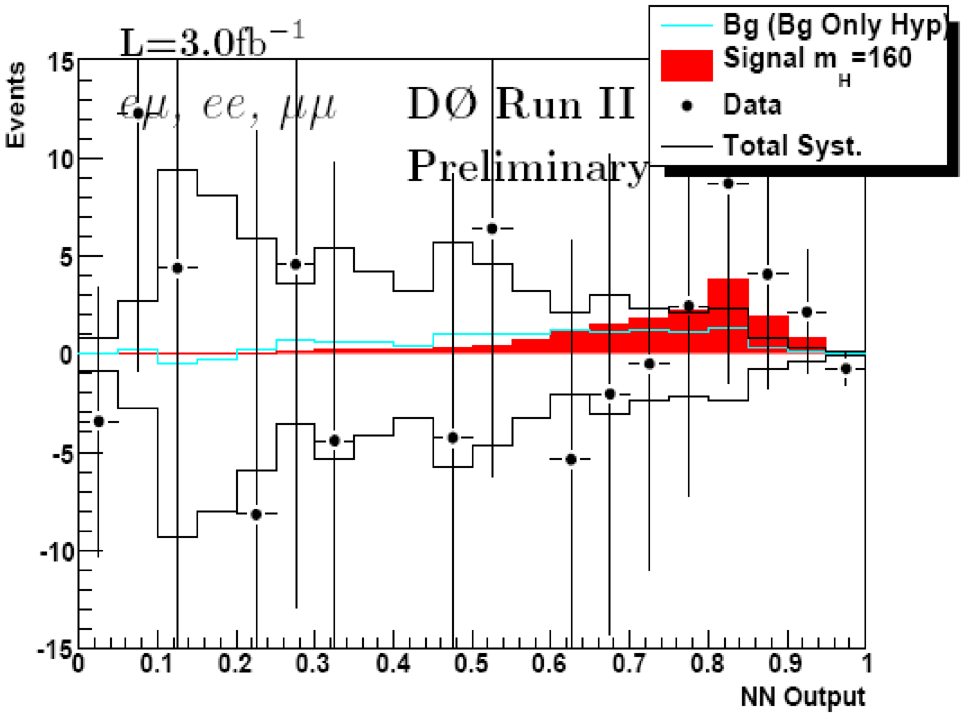
H→WW→ lν lν

Backgrounds are large!

Systematics under control

- but further understanding will improve sensitivity



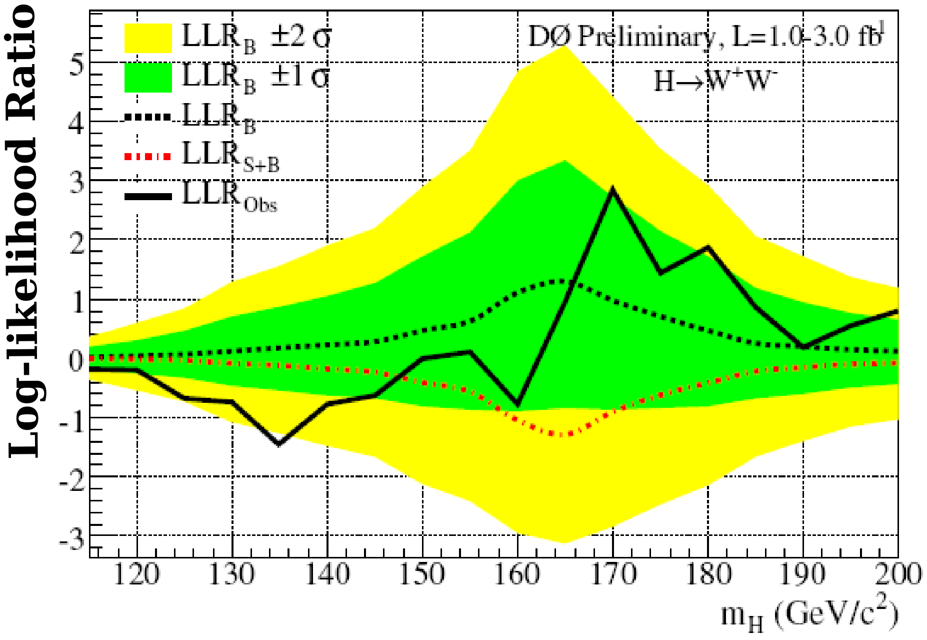


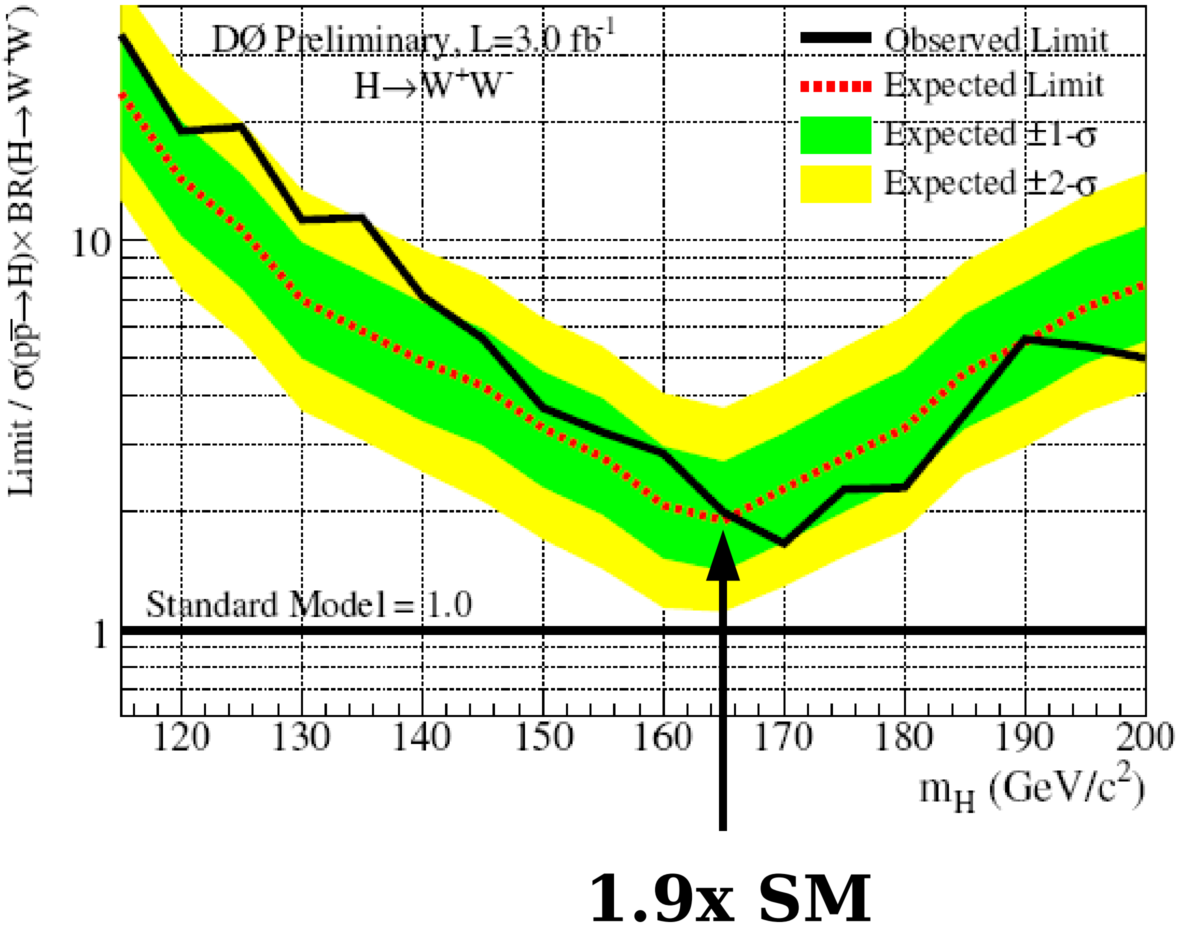
H→WW→ lν lν

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

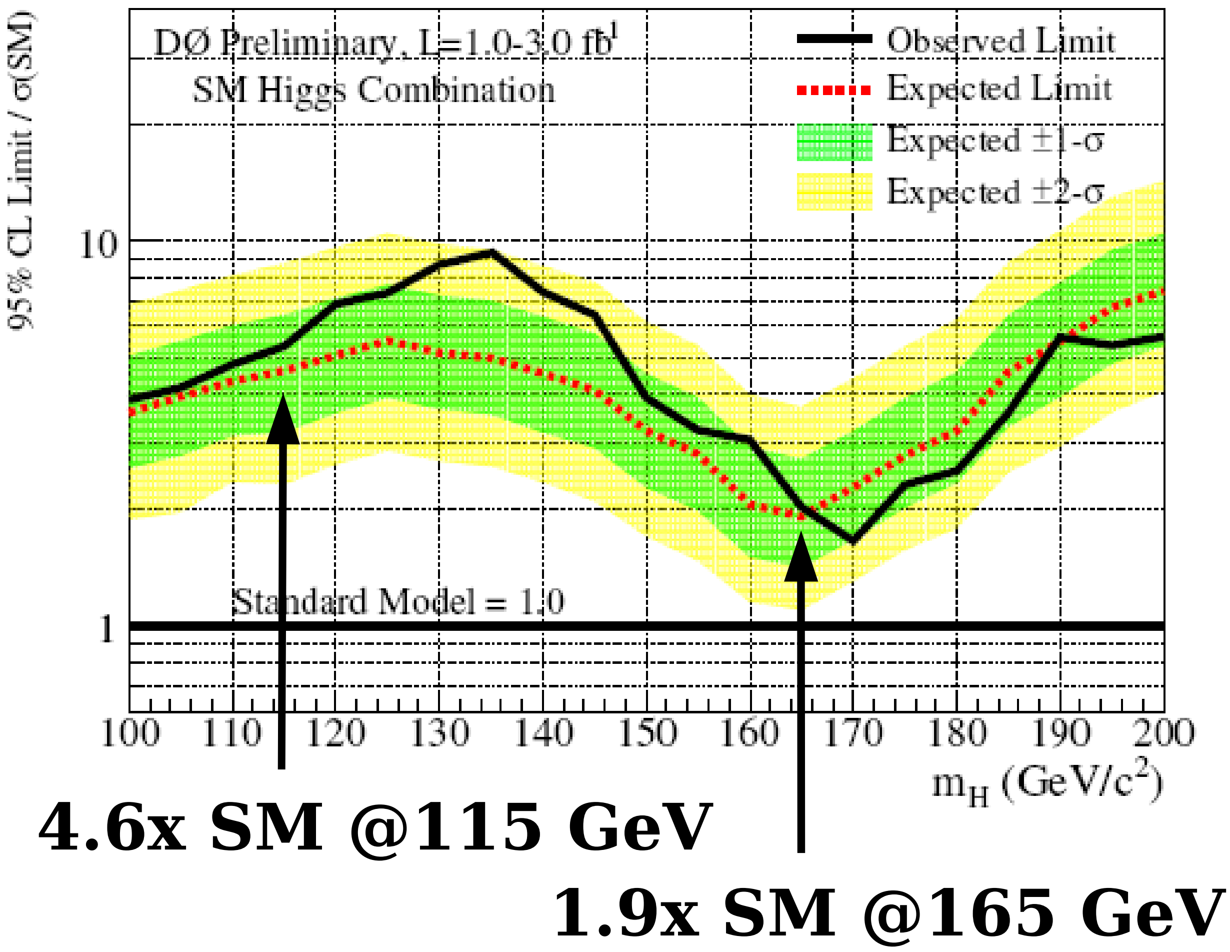
DØ Higgs Combination

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→bb / bb separation
  - muon tagging
  - ...
- **Jet / b-jet resolution**



Jet and b-jet Resolution

Critical for low-mass h→bb searches

- Aiming for 20% improvement

Multiple jet energy corrections

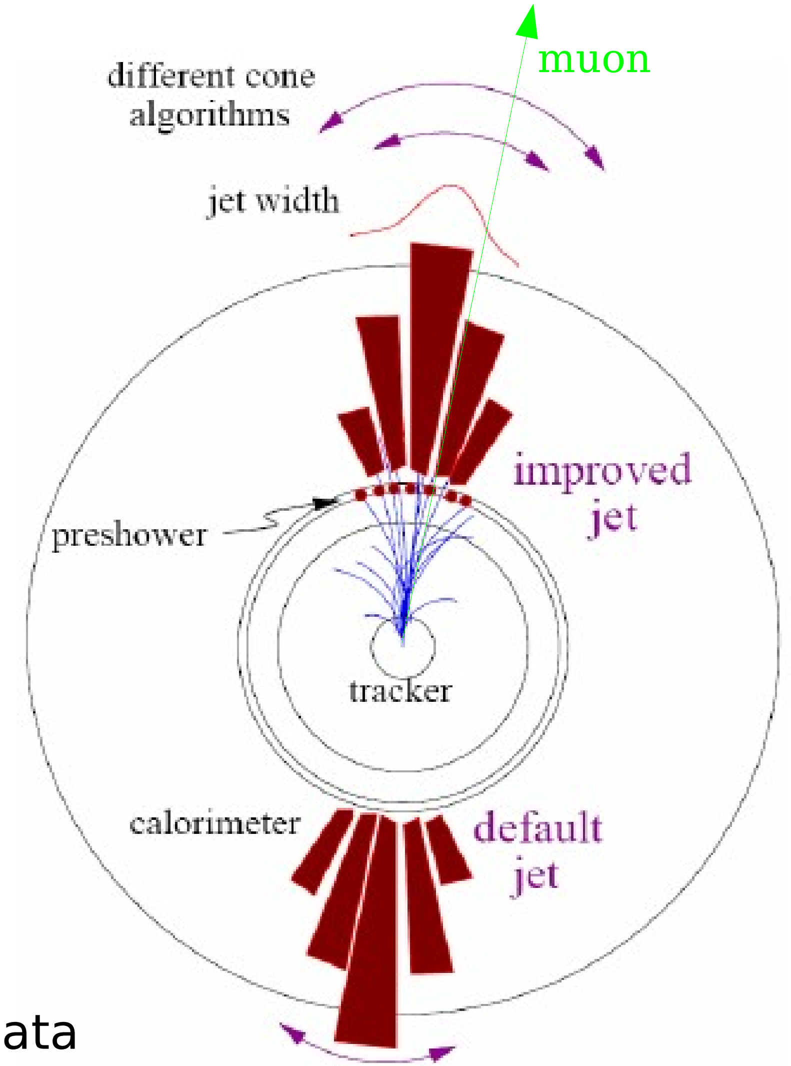
- Jet-width dependence
- Jet cone radii
- Pre-shower energy
- Track-based
- ...

And b-jet specific corrections

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

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

- γ + b-jet, Z + b-jet, di-b-jet balancing



SUSY Higgs

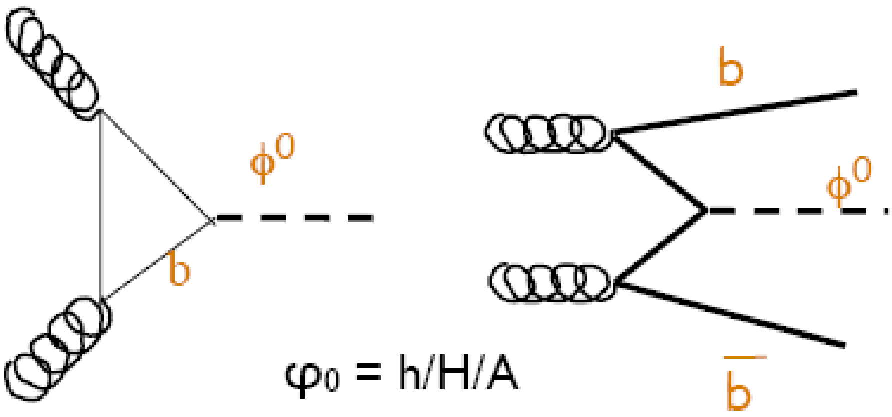
Supersymmetry predicts (at least) **5 Higgs**
- cancel anomalies

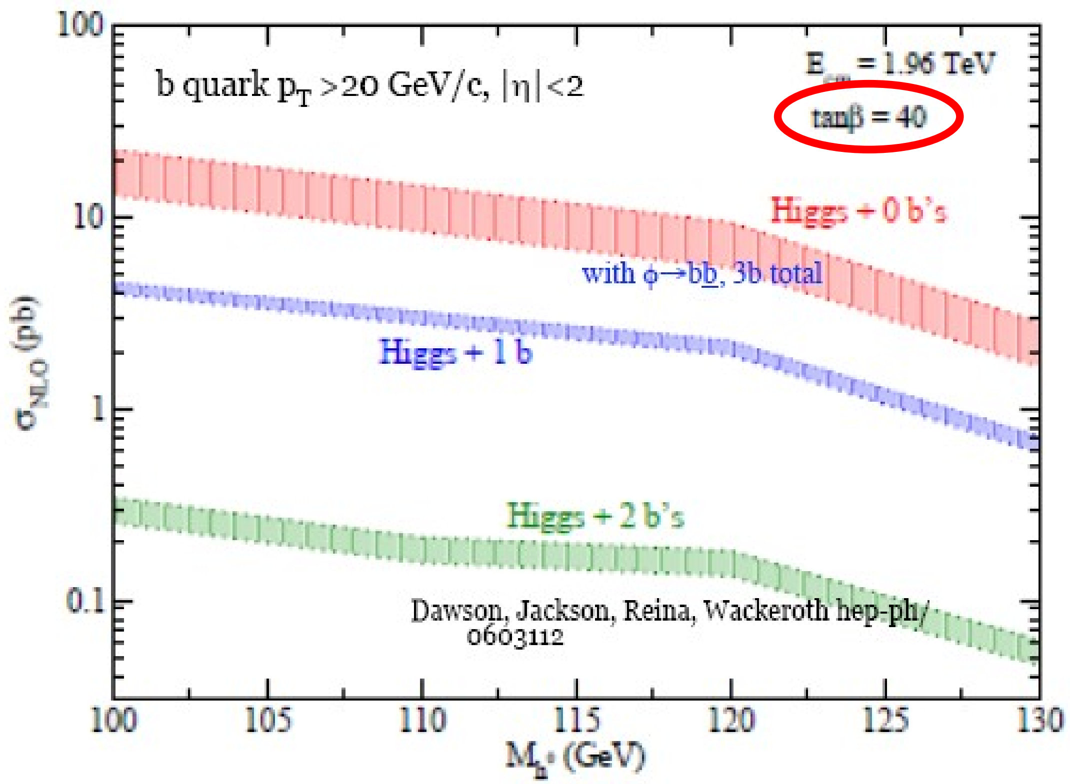
h/H and A typically degenerate: **φ**

Cross-section proportional to *tan²β*
- ~1000x enhancement possible!

tanβ~40 is well-motivated (m_t/m_b)

Dominant decays:
- **bb (90%)**
- **ττ (10%)**

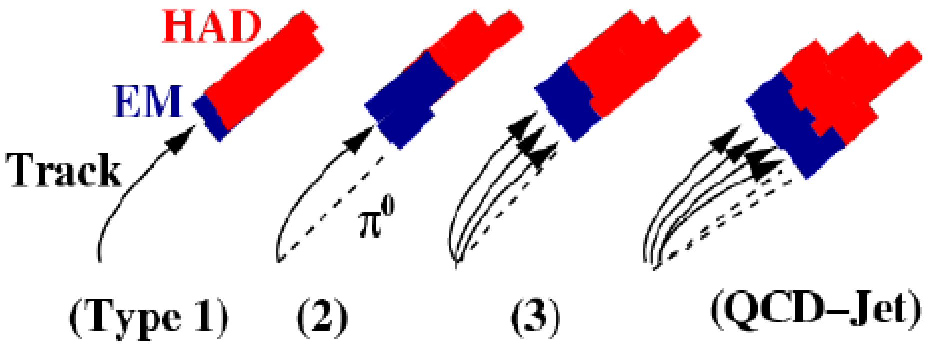




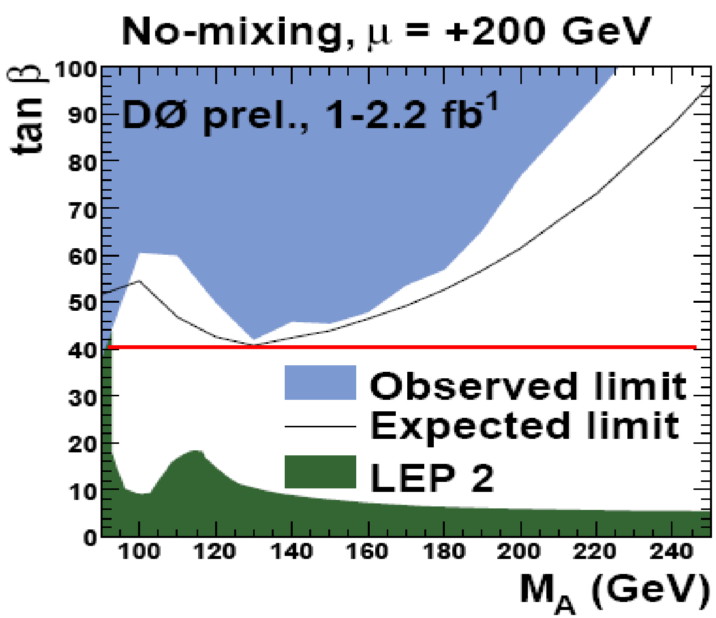
φ→ττ

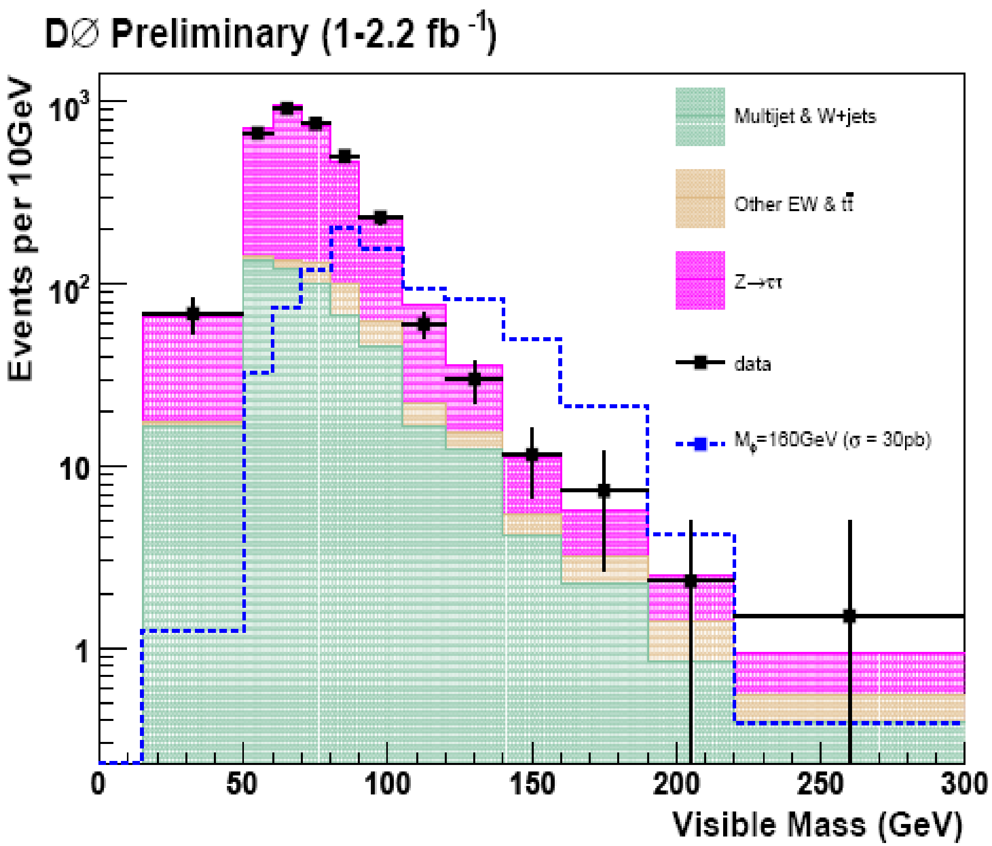
Single-lepton trigger, look for $\mu+\tau_{had}$, $e+\tau_{had}$, $\mu+e$

Reconstruct hadronic taus and reject jets



arXiv:0805.2491



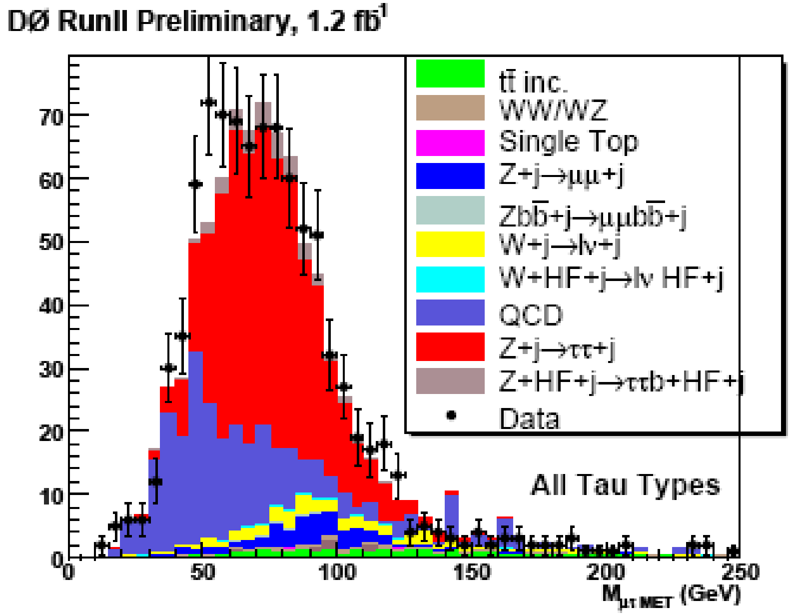


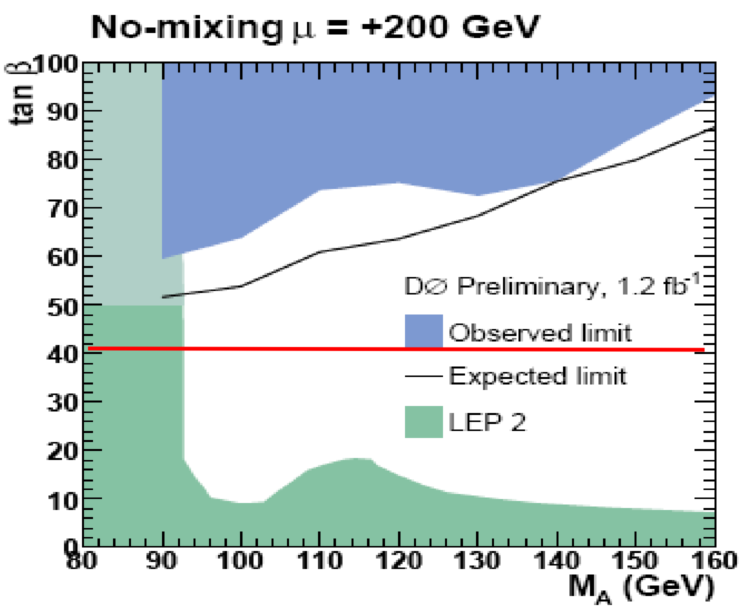
$b\varphi \rightarrow b\tau\tau$

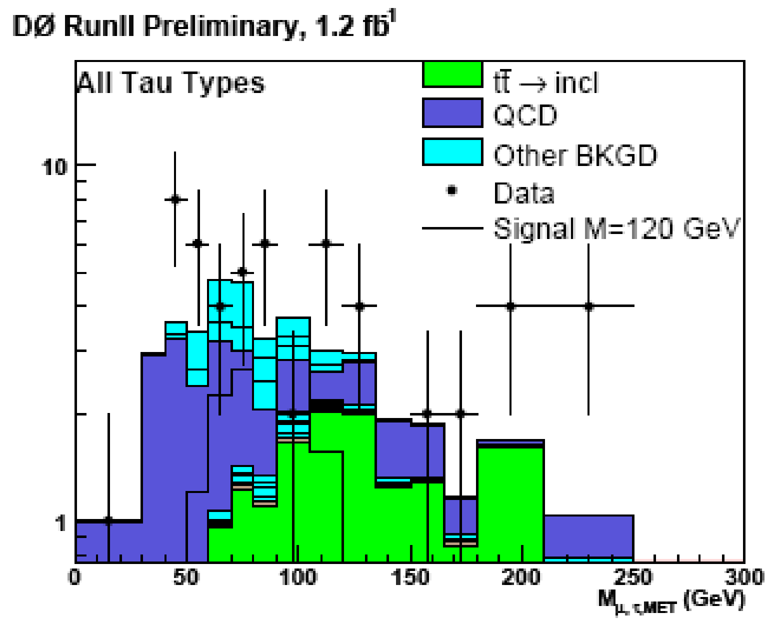
Select μ+τ_{had}+jet events

Apply b-jet tagging

Look at μ+τ_{had}+ME_T invariant mass







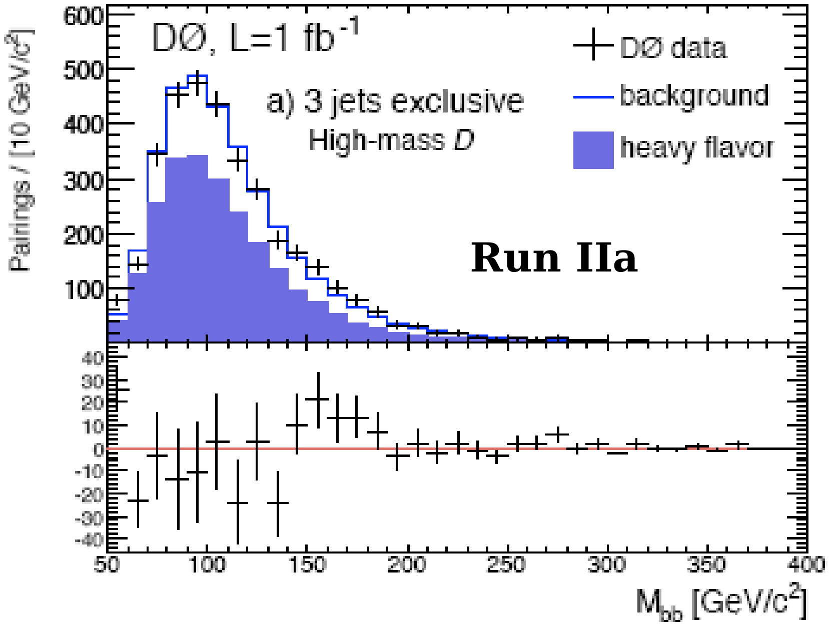
bφ→bbb

Multi-jet trigger, with b-tagging

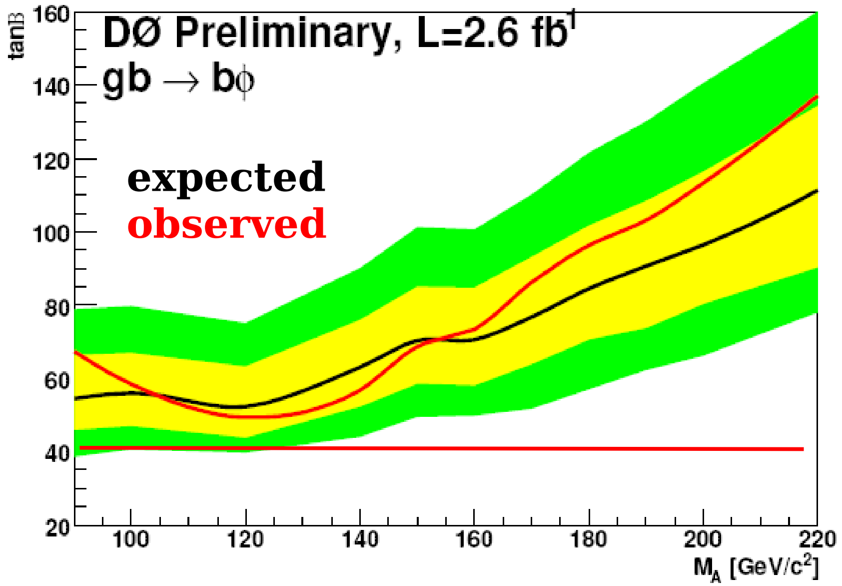
Select **triple-b-tagged** events

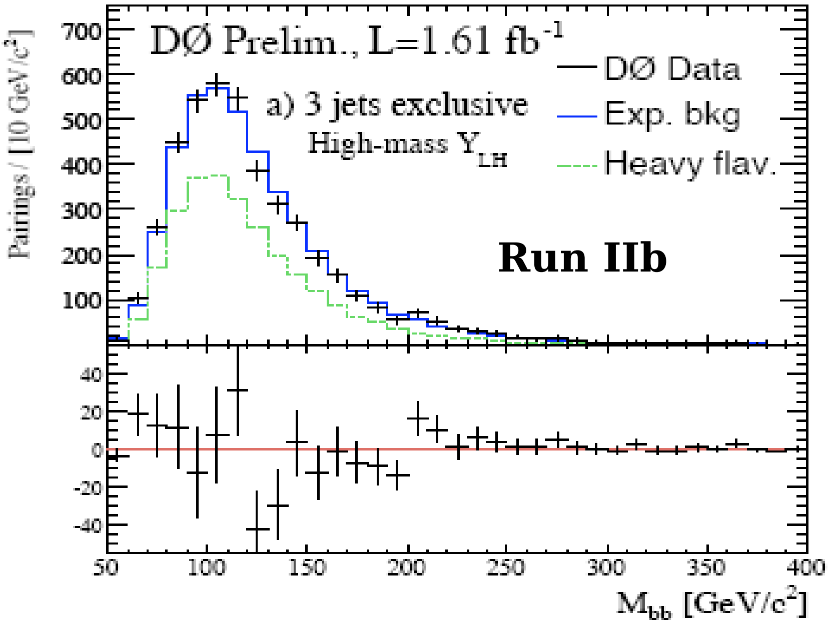
Background to 3 b-tagged signal derived from 2 b-tagged data

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 tanβ, now approaching tanβ~40

- Combination underway

Next talk will discuss the combination with CDF…

Backup

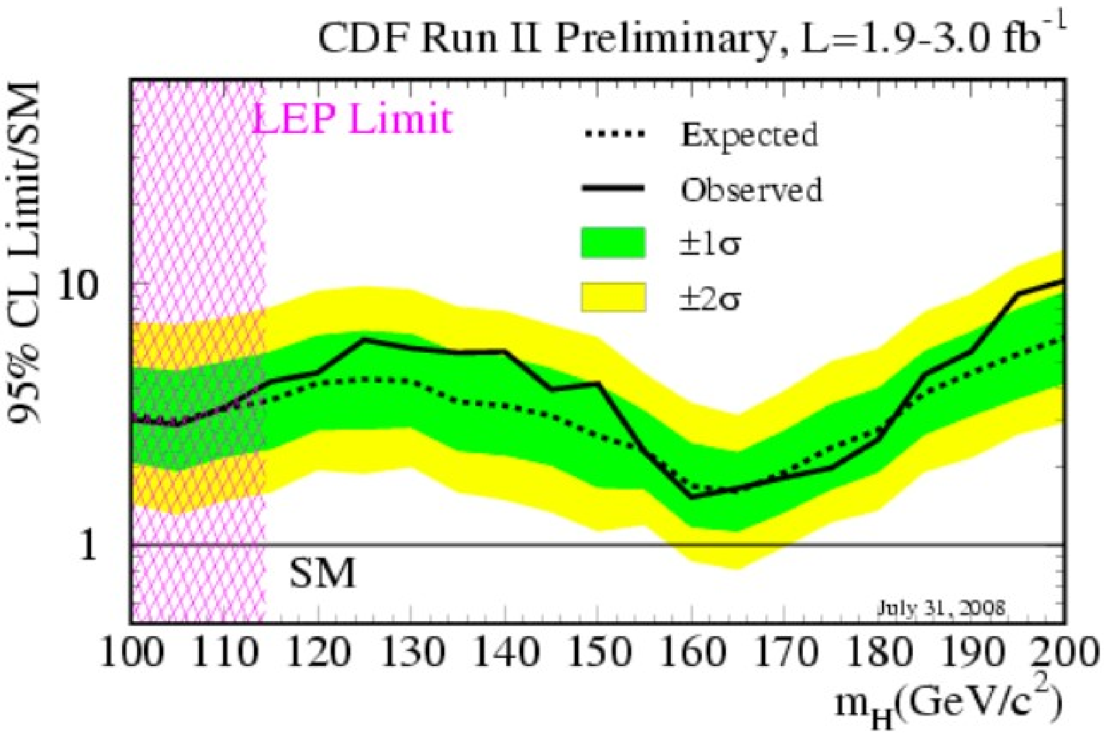
Tevatron Higgs Combination

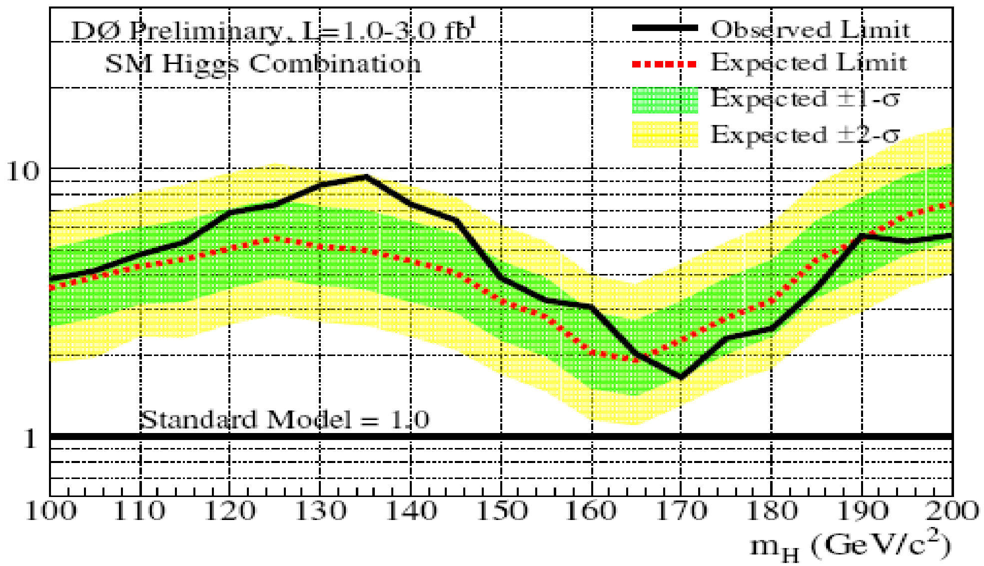
CDF uses Bayesian limit-setting technique (cross-checked by DØ CL_s)

Systematic uncertainties properly correlated between experiments

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

Expected sensitivity <3x SM @115 GeV

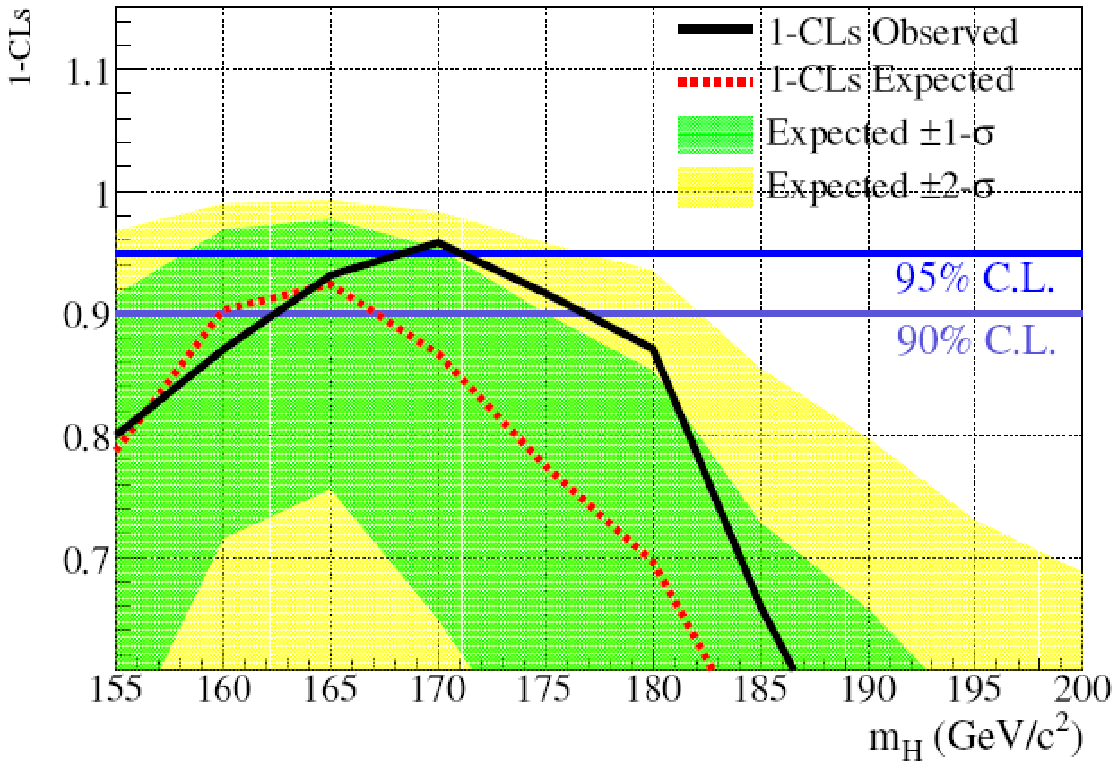




Tevatron Higgs Combination

SM Higgs excluded at 170 GeV !!!

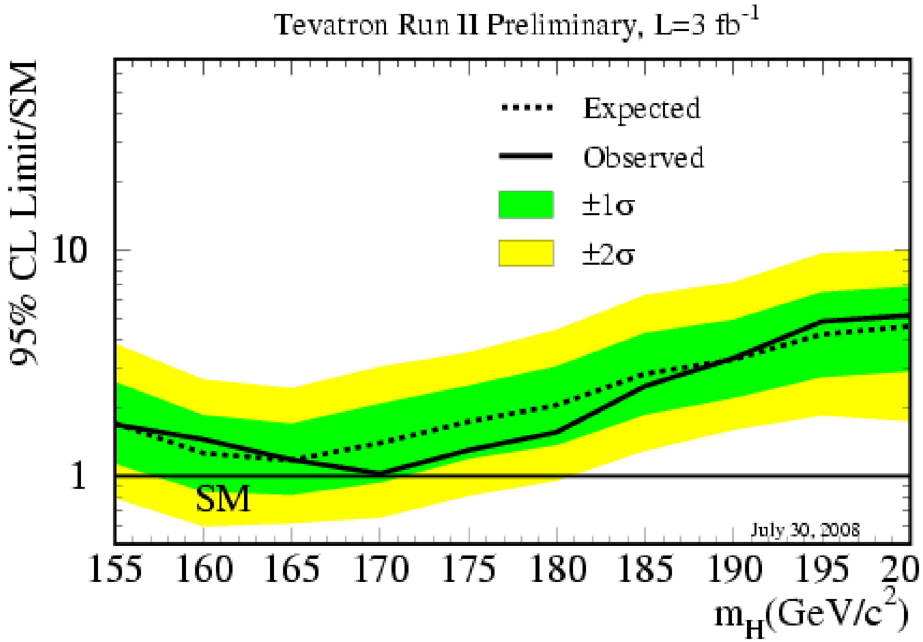
Sensitive to a large range of Higgs masses by Moriond



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



Conclusions

<u>The Tevatron is closing in on the Higgs</u>

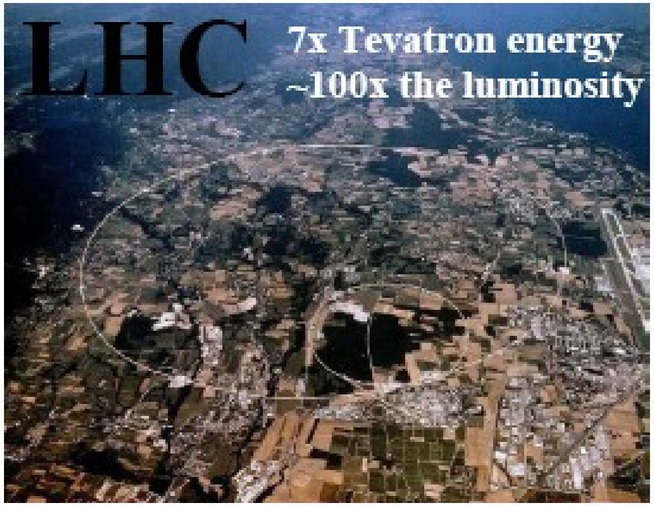
Consistent with EW fits, we have direct evidence against a heavy Higgs…
SM Higgs excluded at 170 GeV !!!

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

Excellent sensitivity to SUSY Higgs at high tanβ, now approaching tanβ~40

- Combinations underway

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



H→WW→ lν lν

All pre-selections kept as loose as possible

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

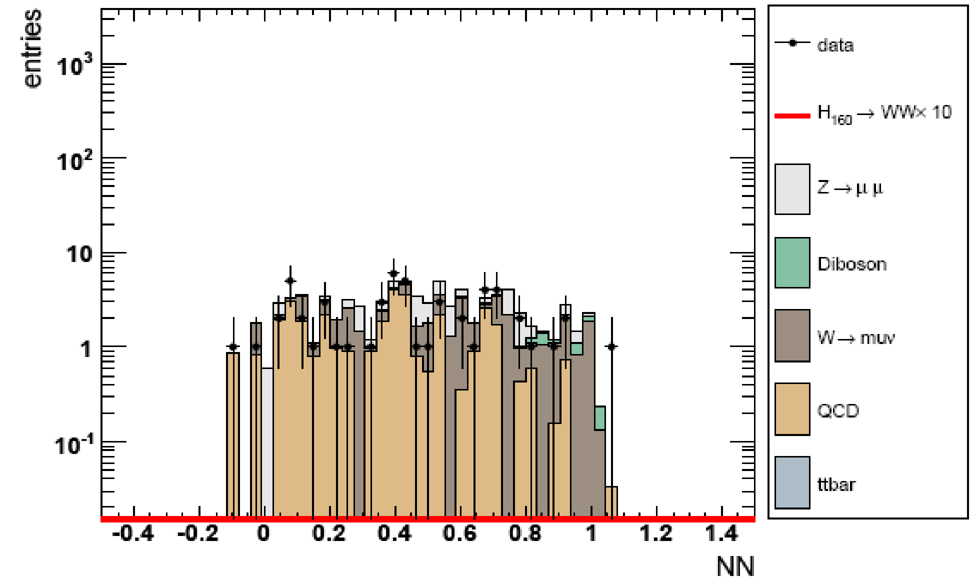
Final state	$e\mu$	ee	$\mu\mu$
Cut 0 Pre-selection	lepton ID, leptons with opposite charge and $p_T^\mu > 10$ GeV and $p_T^e > 15$ GeV invariant mass $M_{\mu\mu} > 15$ GeV $\mu\mu$: $n_{\text{jet}} < 2$ for $p_{\text{T}}^{\text{jet}} > 15$ GeV and $dR(\mu, \text{jet}) > 0.1$		
Cut 1 Missing Transverse Energy $\not{E}_T$ (GeV)	> 20	> 20	> 20
Cut 2 $\not{E}_T^{\text{Scaled}}$	> 7	> 6	> 5
Cut 3 M_T^{min} $(\ell, \not{E}_T)$ (GeV)	> 20	> 30	> 20
Cut 4 $\Delta\phi(\mu, \mu)$	< 2.0	< 2.0	< 2.5

H→WW→ lν lν

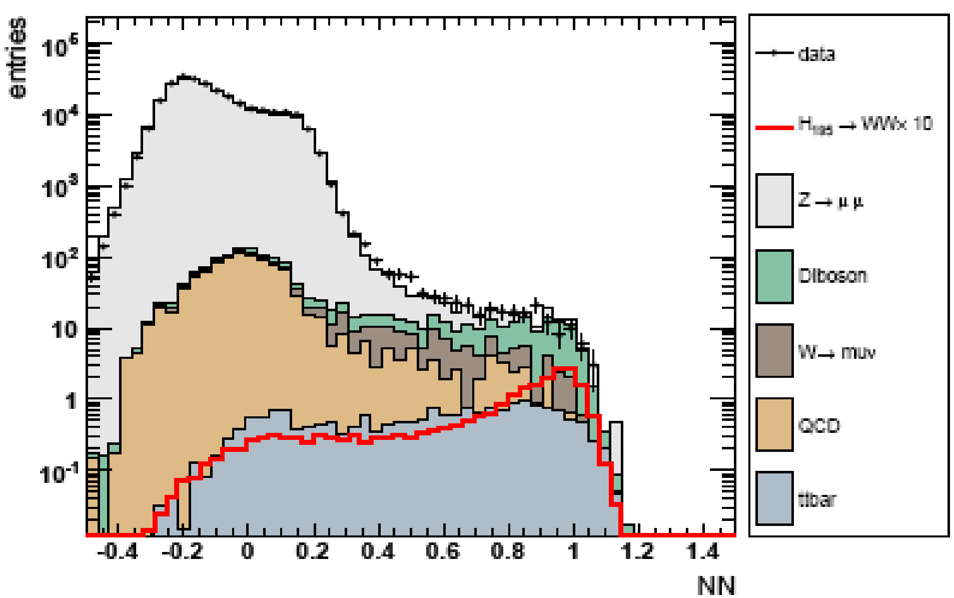
Many cross-checks performed in various other sets of the data/MC
- Like-sign (check W+jets and QCD)
- W+jets selection

Pre-selection NN output
- Check for correlations not modeled in high-statistics Z samples

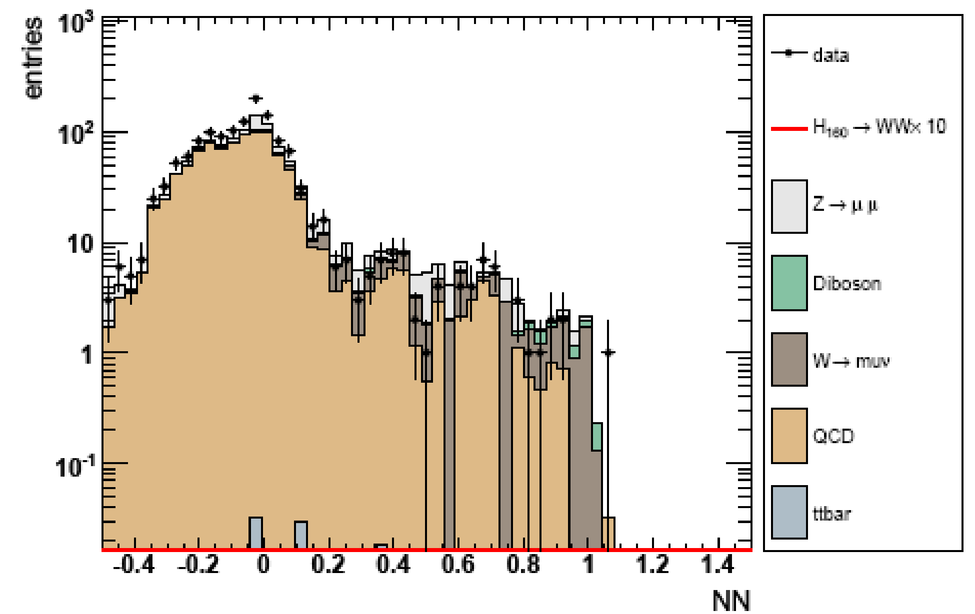
W+jet selection, like-sign



Pre-selection, opposite-sign



Pre-selection, like-sign



Other Models

Could the Higgs be *hiding*?

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