Higgs Searches at LEP, Tevatron and LHC

Particle Physics Course

"Dottorato di Ricerca Internazionale"

LECTURE 2.

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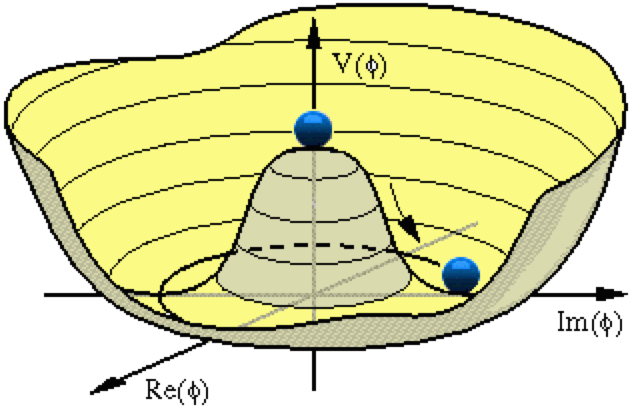
The Standard Model and the Higgs mechanism

“MEXICAN HAT”



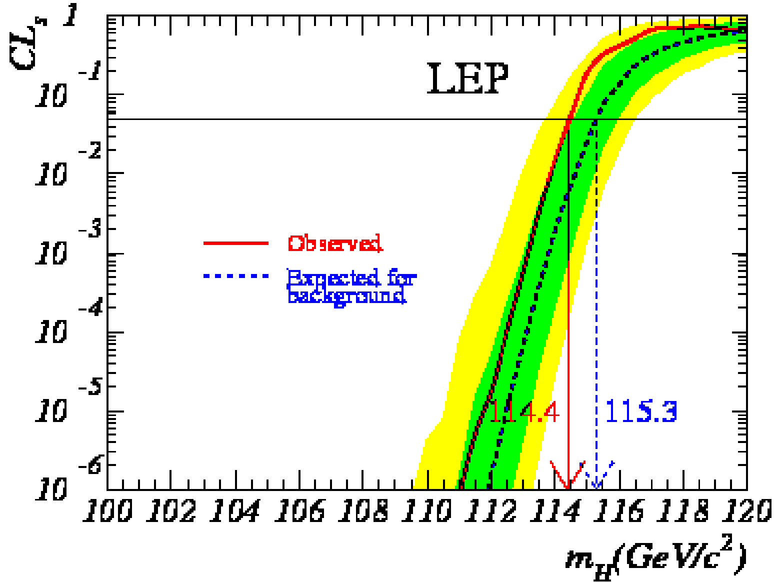
One pseudo-scalar doublet Φ (4 degrees of freedom)

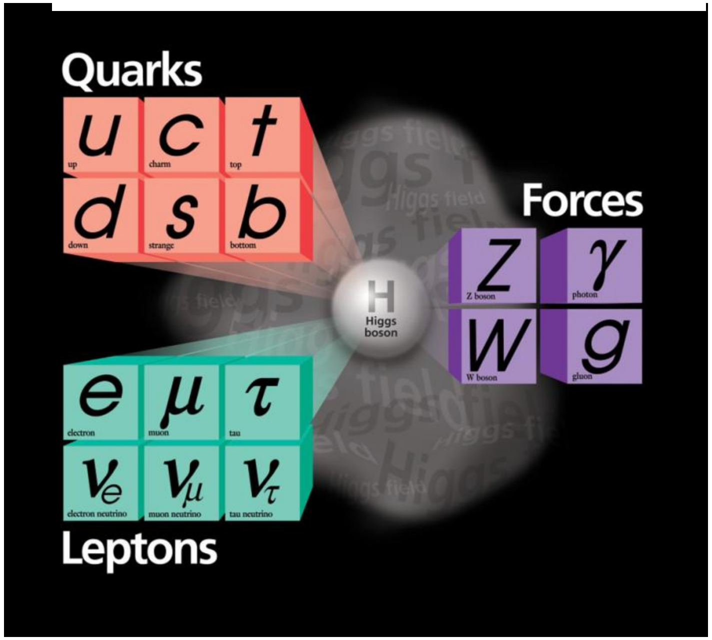
$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 ; \quad \mu^2<0 \quad \lambda>0$$

After spontaneous symmetry breaking:

- **$W^\pm$ and Z acquire masses (3 degrees of freedom)**
- **the last remaining degree of freedom (4-3=1):**

  scalar CP-even Higgs of unknown mass





After the LEP limit (m_H>114.4), the Higgs hunting requires an higher energy Collider !

What do we know on Higgs mass

Precision electroweak data are sensitive to Higgs mass

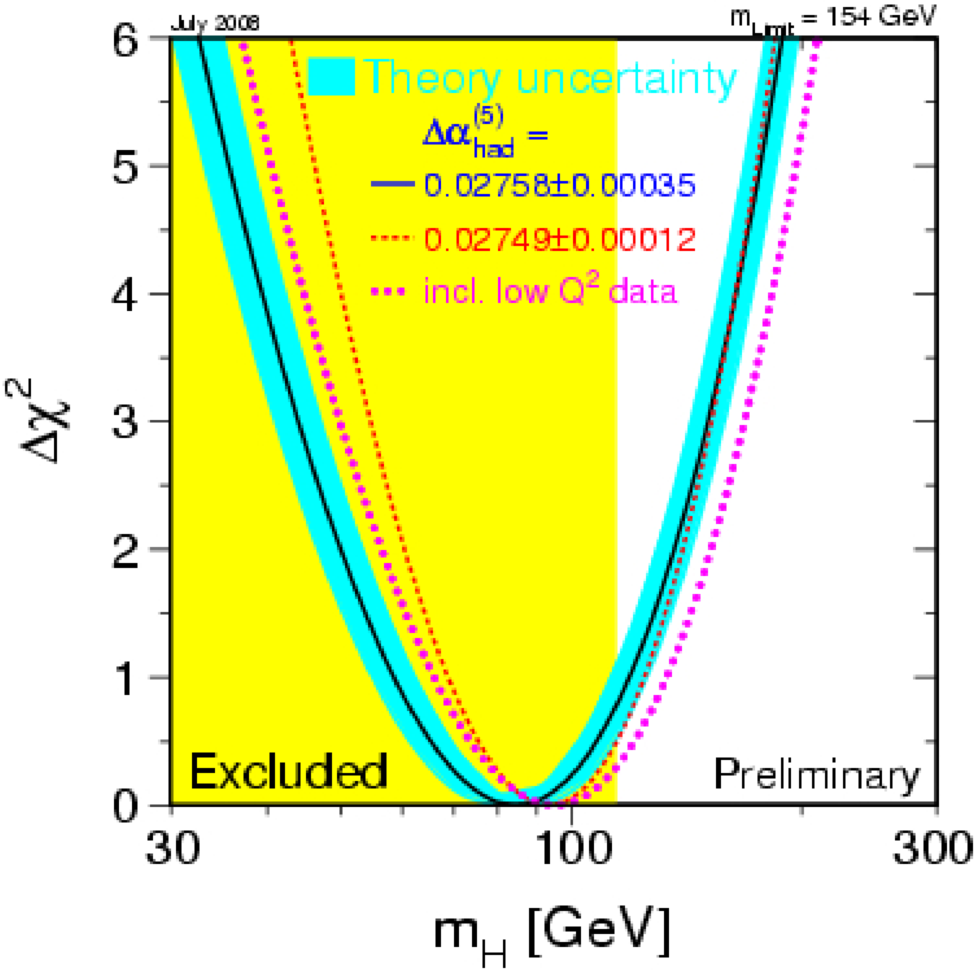
$$m_W = \left(\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\right)\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

$\Delta r = f(m^2_{top}, \log m_H)$

Global SM electroweak fits provide (recent) upper limit :

$M_H = 91\pm^{45}_{32} < 186$ GeV @ 95% C.L.

(July 2008, with recent Tevatron results)



After the LEP limit (m_H>114.4), the Higgs hunting requires an higher energy Collider !

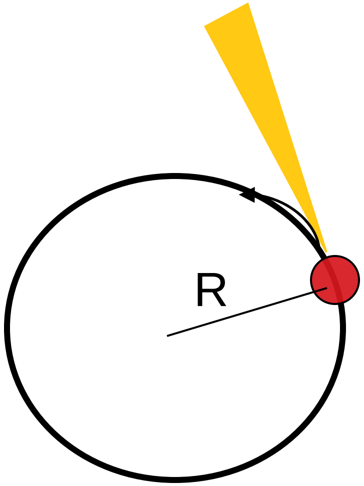
What type of particle to store in a Collider?

- Particles must be
  - **charged**
    - accelerated by electric fields (Energy = charge * Voltage-difference)
    - steered and focused using magnetic fields ($p = q\ 0.3\ R\ B$)
  - **long lived**
    - best : infinite life-time
    - but : due to Lorentz factor $\gamma\tau$, the life-time in the accelerator can be reasonably long
    - example :
      - **Pions**, $\tau=2.6\times10^{-8}$ sec, E=200 GeV, $\gamma = E/m = 200/0.140 = 1428.6$, $\gamma\tau = 0.04$ msec, $v \cong c$, $\Rightarrow$ average distance travelled = $c\ \gamma\ \tau$ = 11 km, good enough for fixed target experiments (**CERN, PSI,...**)
      - **Muons**, $\tau=2.2\times10^{-6}$ sec, E=200 GeV, m = 0.1 GeV/c^2 $\Rightarrow$ $\gamma\tau = 4.4$ msec !, average distance travelled = **1320 km!** (there are ideas for a **muon collider!**)

- In practice for colliders up to now:
  - **electrons, anti-electrons, protons, anti-protons**

Lepton vs Hadron Colliders

Synchrotron Radiation



- Energy loss per revolution

$$\Delta E = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{2\pi R} \qquad \beta = \frac{\mathrm{v}}{c} \qquad \gamma = \frac{\mathrm{E}}{m} \qquad R = \text{orbit radius}$$

$$\Delta E[GeV] = 5.7\times 10^{-7}\frac{E^4[GeV]}{R[km]}$$

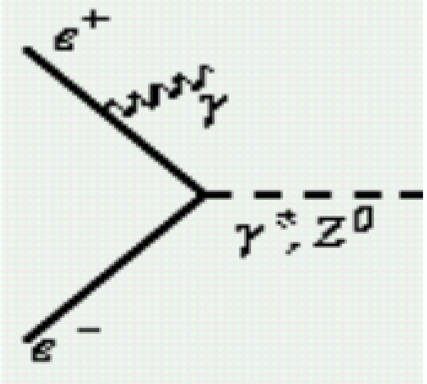
- Example : LEP, $2\pi R$=27km, E=100 GeV (in 2000)
  - **ΔE = 2 GeV!!**
  - LEP at limit, need more and more energy just to compensate energy loss

- Note : for ultrarelativistic protons/electrons ($\beta \simeq 1$)

$\Delta E[p] / \Delta E[e] = (m_e/m_p)^4 =$ **10^{-13} !!**

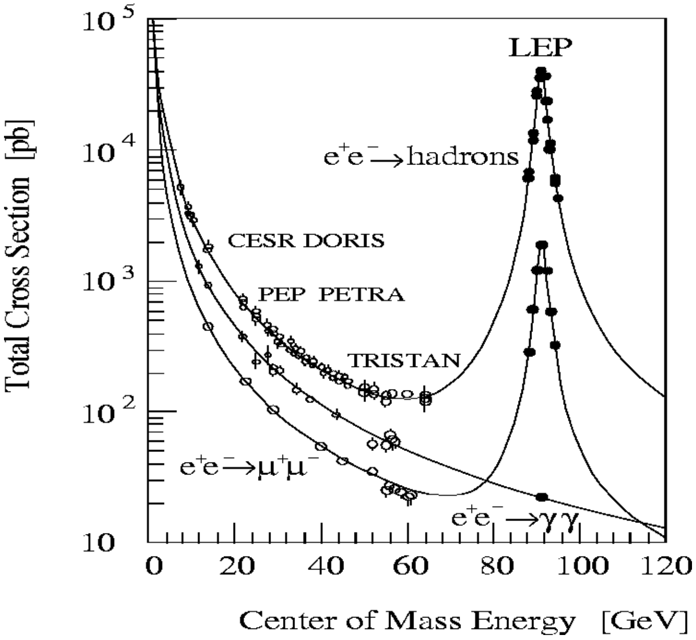
How much beam energy is really available for producing new particles?

- In an e^+e^- collider :
  - practically all of it
  - However: Photon radiation in the initial state can reduce the effective E_{CM}
  - particularly important when close (in energy) to a resonance



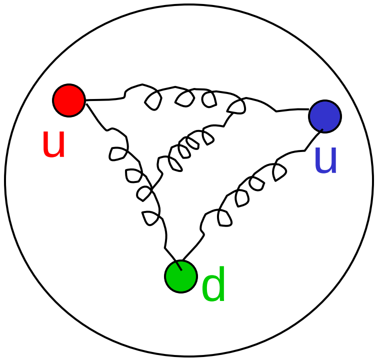
- Advantages:
  - energy very precisely adjustable, for example, to be at a resonance (e.g. Z: 91 GeV, Upsilon: 9.46 GeV) where the cross section is large

- Disadvantages:
  - When looking for new particles with unknown mass: Have to scan "manually" the beam energy

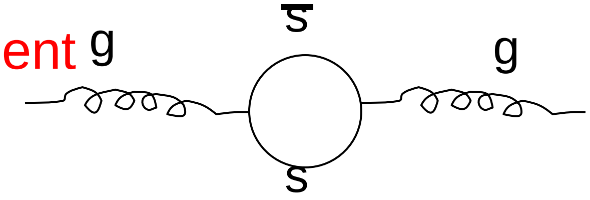


Proton structure

- (Anti-) Protons are a quark-gluon soup
  - 3 valence quarks bound by exchange of gluons
  - Gluons are colored and interact with other gluons
  - Virtual quark pair loops can pop-up generating additional quark content (sea-quarks)
  - Proton momentum is shared among all constituent partons (quarks& gluons)



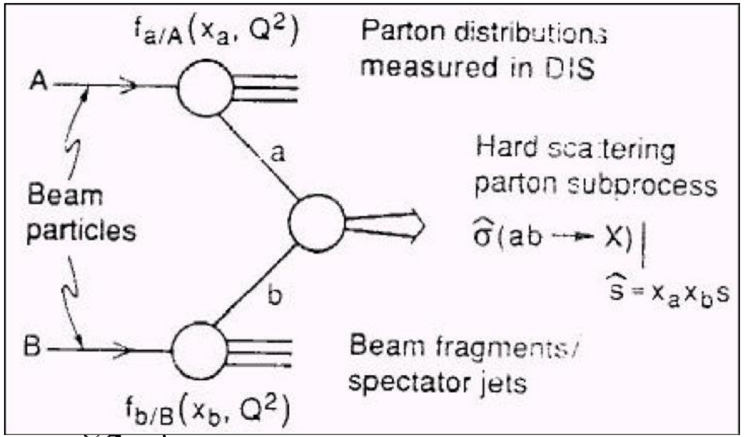
Proton

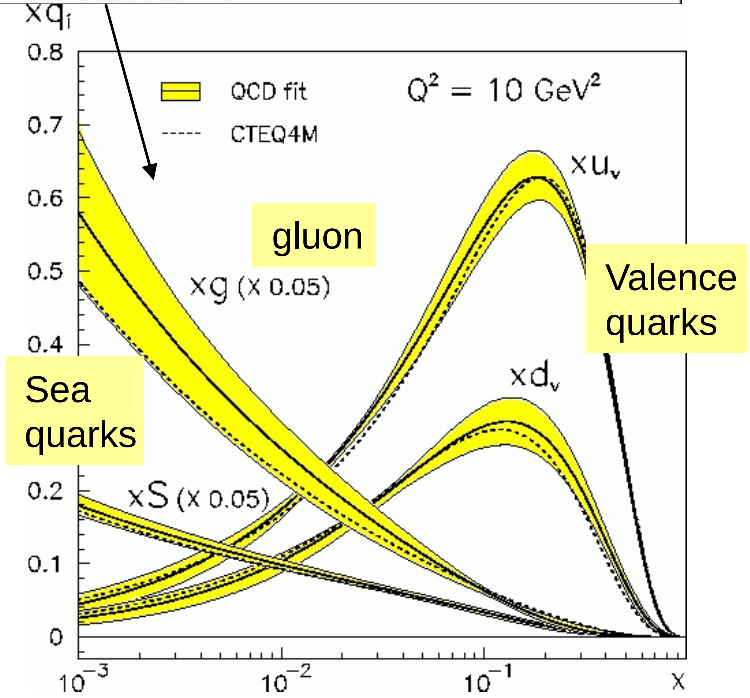


Virtual quark loop

How much beam energy is really available for producing new particles?

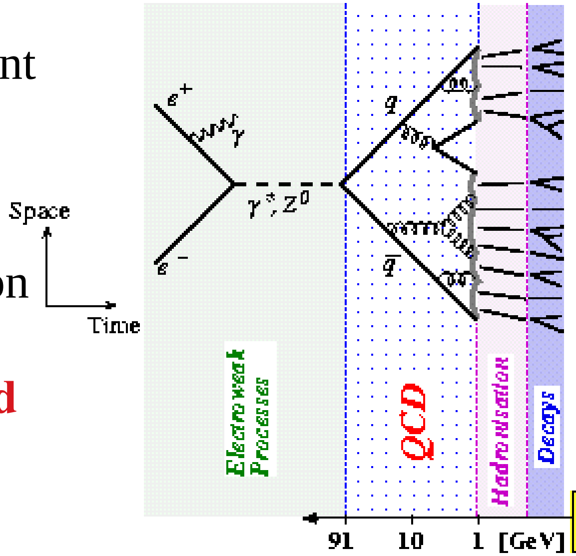
- In an proton collider :
  - hard interaction due to partons
  - **Effective $E_{CM}^2 = x_a \, x_b \, E_{CM}^2$**
  - $x_a, x_b << 1$
- Advantages:
  - because in every collision the x_i are chosen "at random", there is a natural scan of effective E_{CM} : good for exploration of new energy regime (for new particles)
- Disadvantages:
  - effective E_{CM} not adjustable by operator
  - since in general $x_a \neq x_b$: centre-of-mass system boosted w.r.t. to lab system



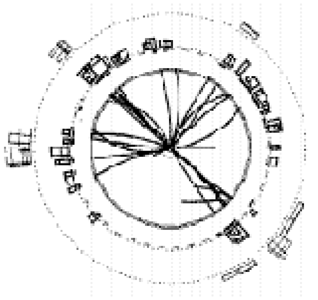


Lepton vs Hadron Colliders

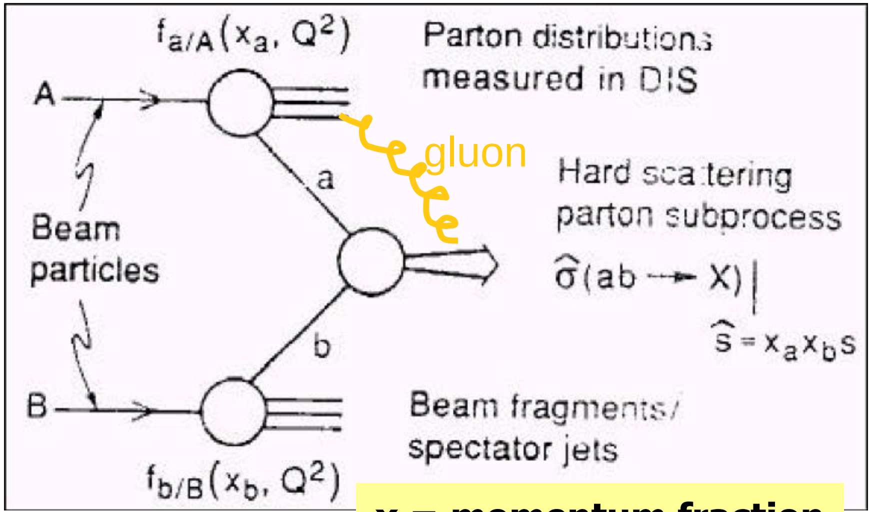
- take e^+e^- annihilation to quarks
  - e^+, e^- are **point-like** particles (to our present knowledge)
  - colliding particles do **not carry colour** charge ⇒ no interference between initial and final state because of strong interaction (gluon emission)
  - ⇒ theoretical calculations are **“easy” and precise**



Typical Momentum Transfer at LEP-1

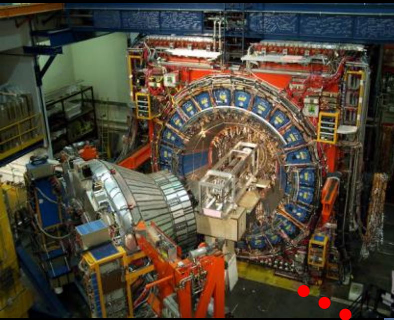


- take proton-proton collisions:
  - protons are **made out of quarks and gluons**, actual interaction is between these partons
  - parton distributions cannot be computed from first principles, only determined from experiments
  - colliding particles carry **colour charge** ⇒ interference
  - ⇒ theoretical calculations are very **“difficult”, and not very precise**

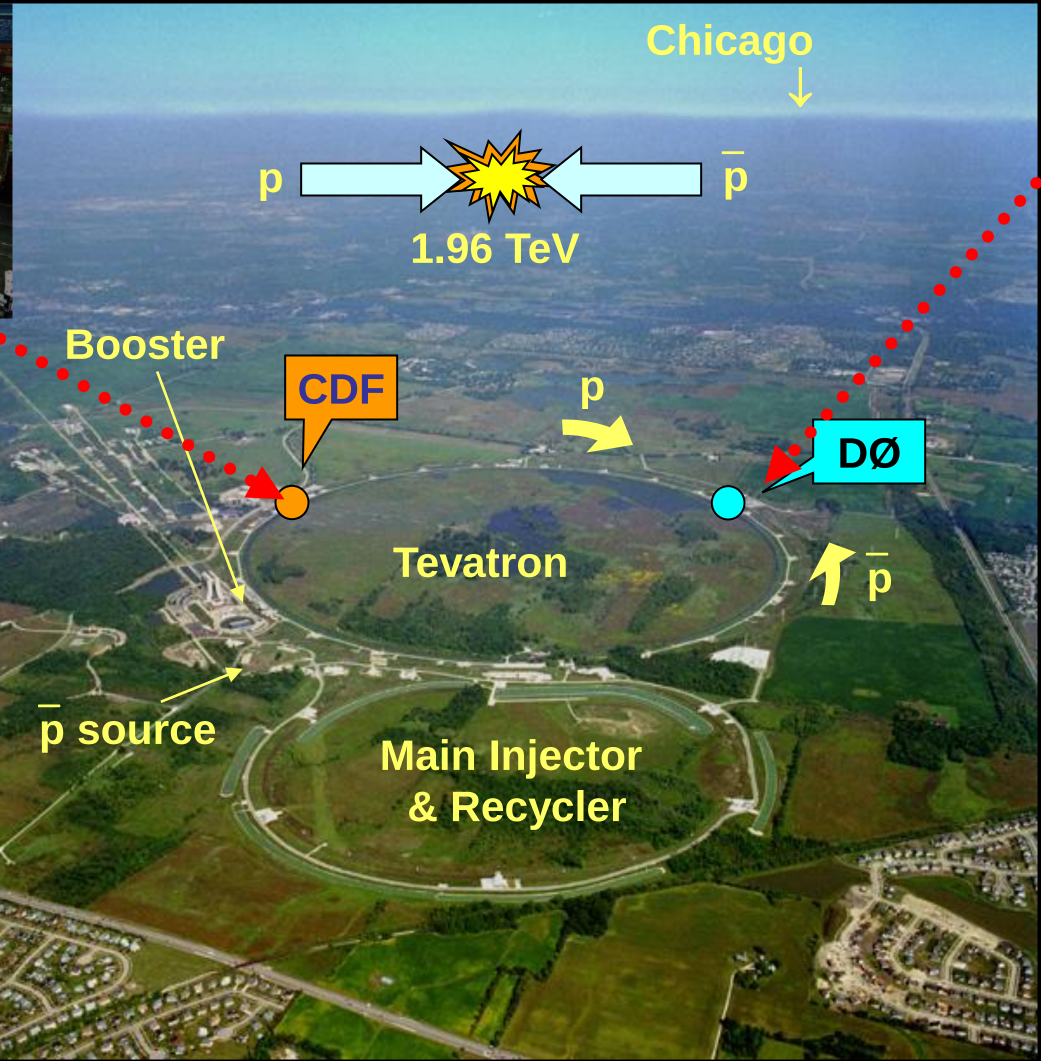


x = momentum fraction

Fermilab TeVatron



Run I
1992-1996
E_{CM} = 1.8 TeV
~120 pb^{-1}
(0.63 TeV ~600 nb^{-1})



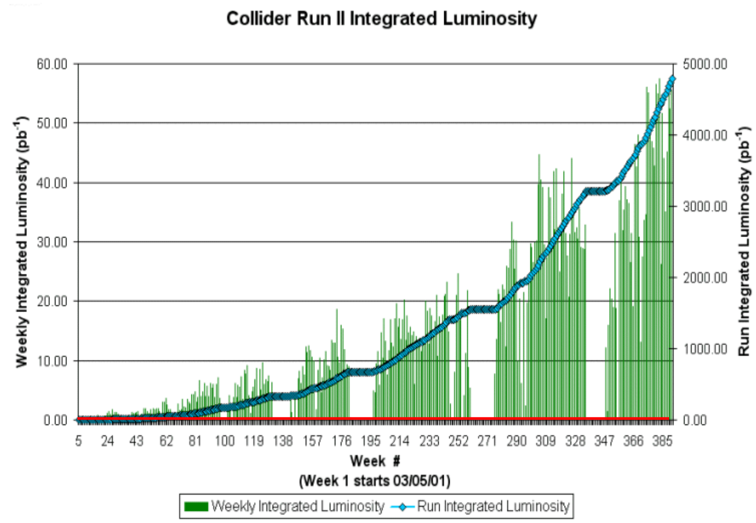
Run IIa
2001-2005
E_{CM} = 1.96 TeV
~ 1.2 fb^{-1}

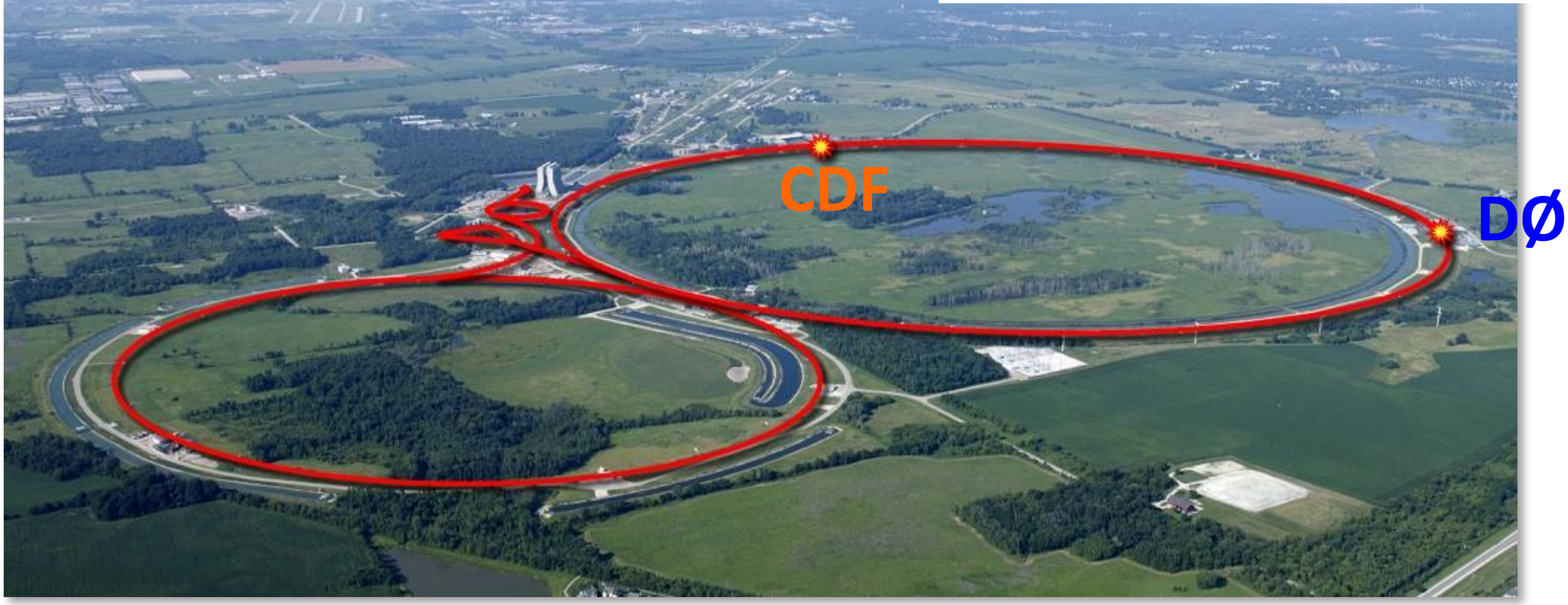
Run IIb
2006-2009
E_{CM} = 1.96 TeV
expected~8 fb^{-1}

Tevatron Collider

Running well…

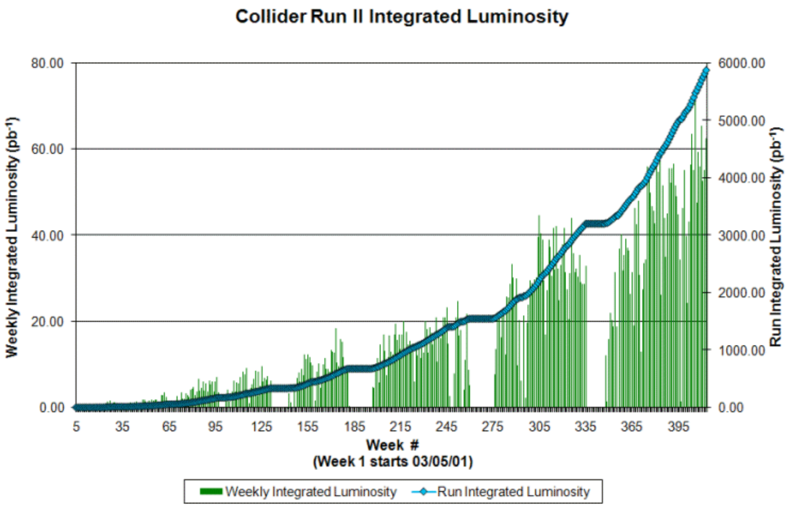
- surpassed design instantaneous luminosity
- delivered over 5 fb^{-1} to each experiment

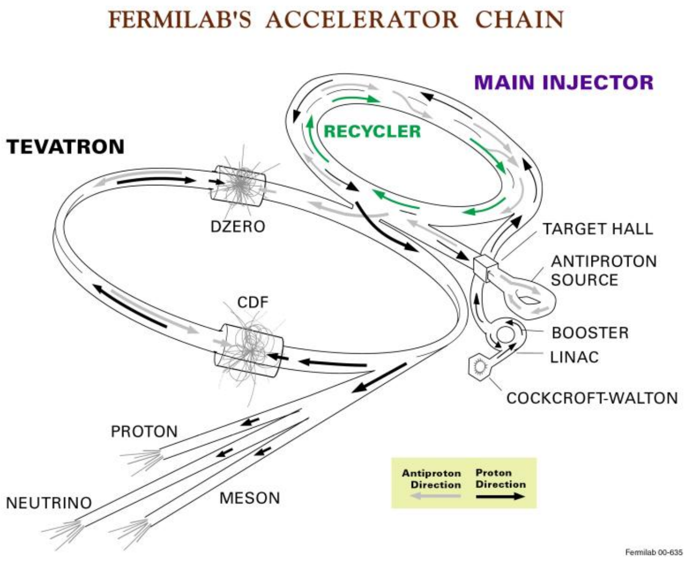




THE TEVATRON AT FERMILAB

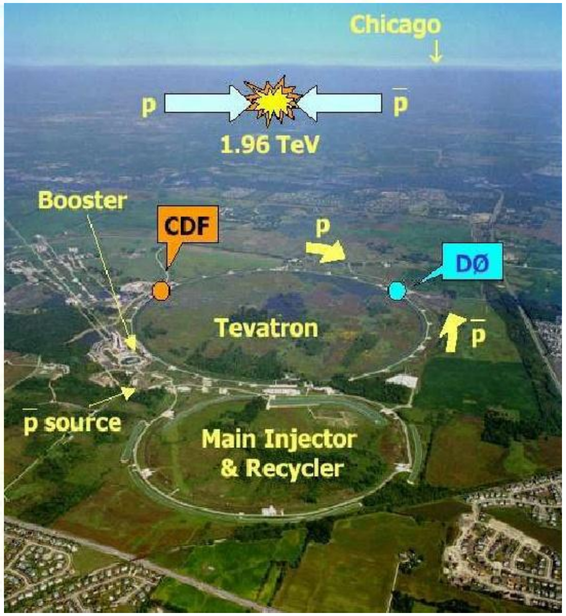
- *$p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV*
- Peak luminosity ≈360 × 10^{30}cm^{-2} s^{-1}
- Tevatron delivered ≈5.5 fb^{-1}
- DØ collected ≈4.7 fb^{-1}
- CDF collected ≈4.5 fb^{-1}
- Tevatron is performing extremely well
  - Integrated over 250 pb^{-1} of data in January 2009
  - Expected 6-8 fb^{-1} by end of 2009
  - Run in 2010

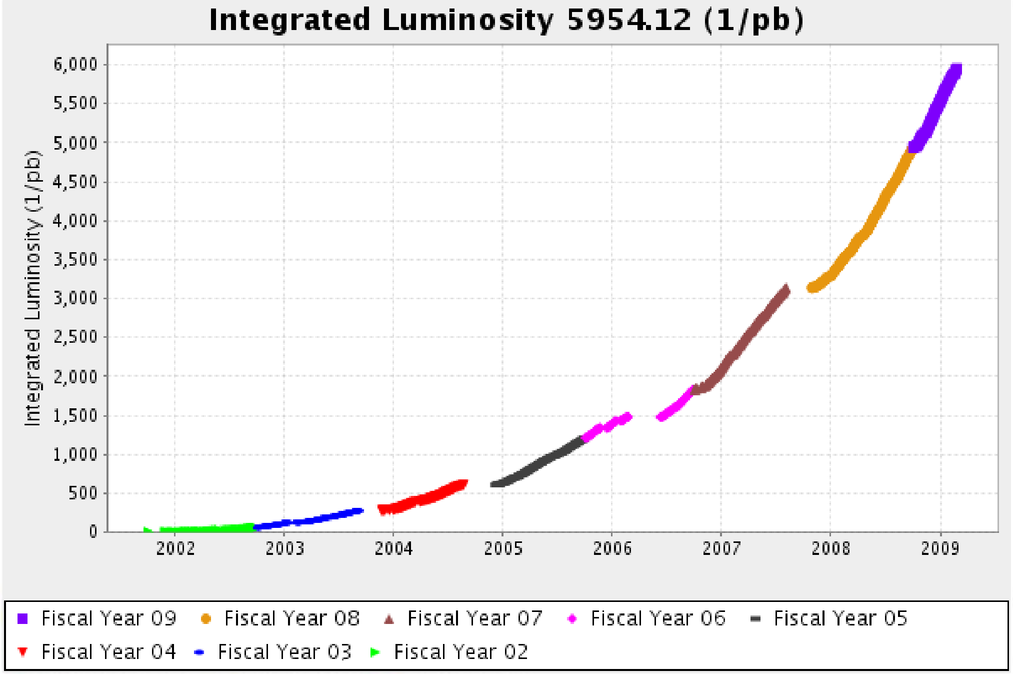




Tevatron Accelerator

	1992-1996	2001-2006	2006-?
	Run I	Run IIa	**Run IIb**
Bunches in Turn	6 6	36 36	**36 36**
s (TeV)	1.8	1.96	**1.96**
Typical L (cm^{-2}s^{-1})	1.6 10^{30}	1x10^{32}	**2.8 10^{32}**
|Ldt (pb^{-1}/week)	3	15-20	**50-60**
Bunch crossing (ns)	3500	396	**396**
Interactions/crossing	2.5	2.5	**7.0**





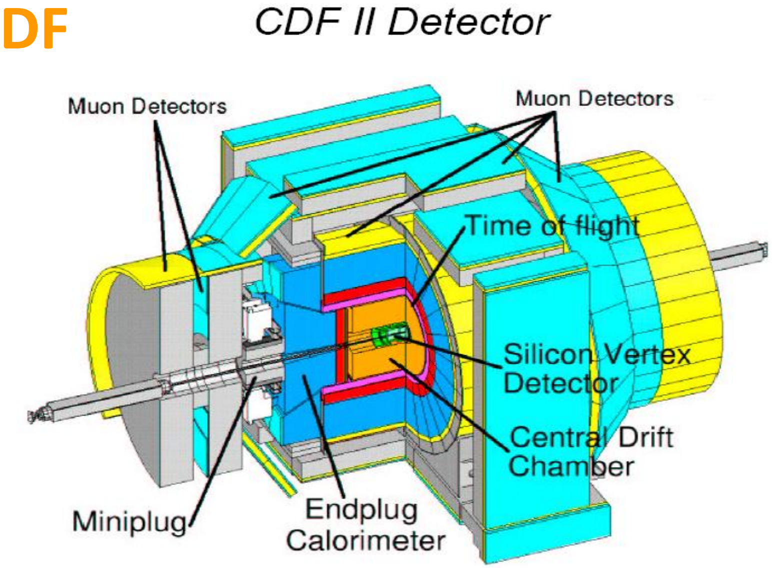
Current status:

- Typical instantaneous luminosity: >3.0x10^{32} cm^{-2}s^{-1}

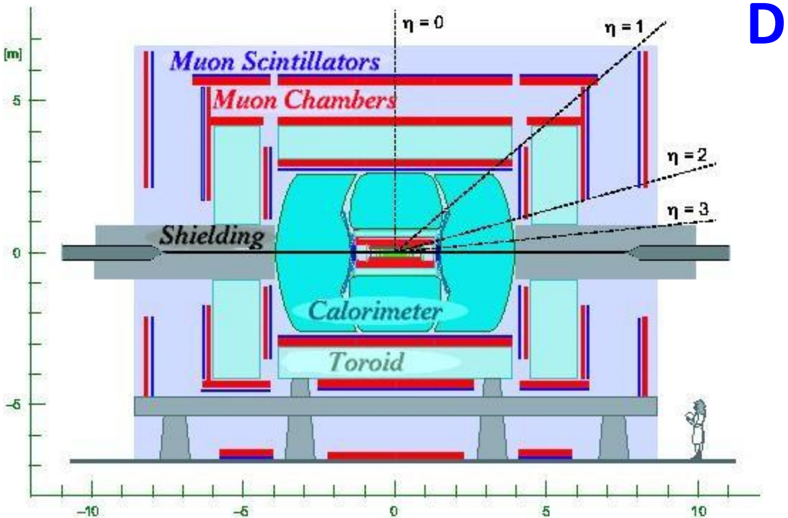
  Record inst. lum.: 3.6x10^{32} cm^{-2}s^{-1}
- Integrated lum./week: ~60-70 pb^{-1}
- Delivered ~6 fb^{-1}

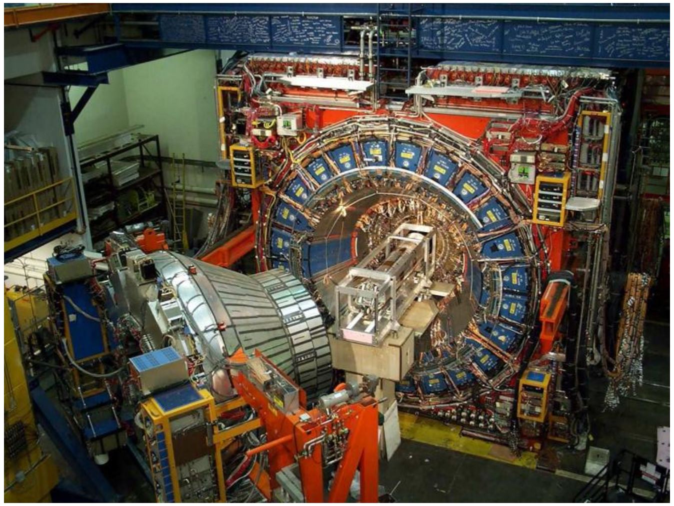
The Detectors

CDF



DØ

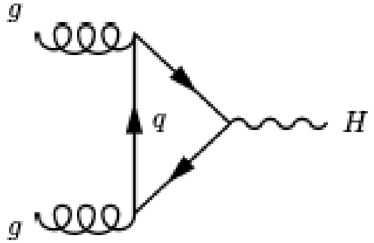


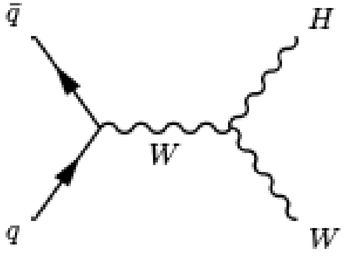


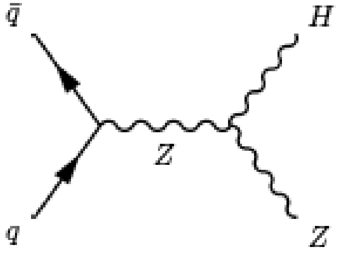
- ◆Large tracking volume
- ◆Vertex trigger
- ◆Large trigger bandwidth

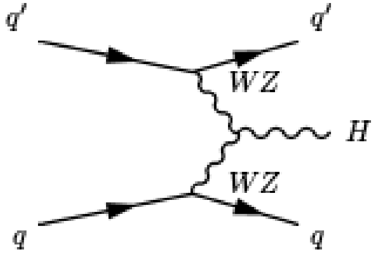
- ◆Compact tracker,
- ◆Large muon coverage

Higgs Production



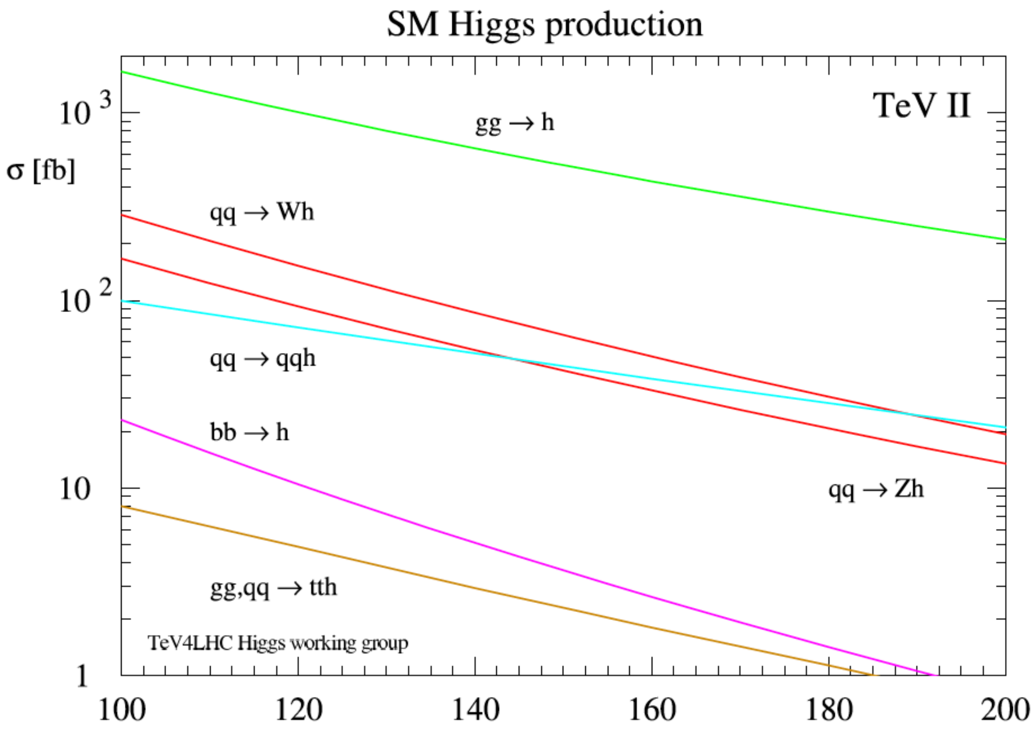




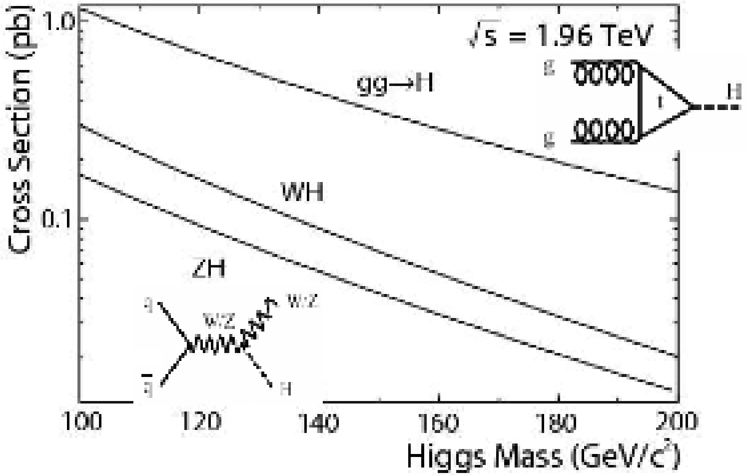


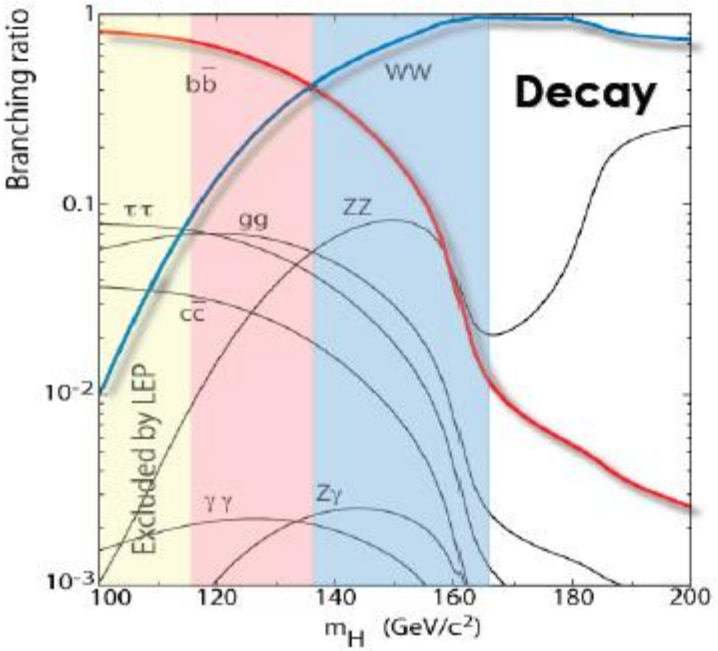
- dominated by gg→H,
- sizeable contributions from WH/ZH
- use all contributions in analyses

$\sigma\left(p\bar{p}\rightarrow H+X\right) \approx$ 1 pb @ 115 GeV



SM Higgs search at Tevatron





- **Production**
  1. **Gluon fusion** (0.8 ~ 0.2 pb)
  2. **WH associated production** (0.2~0.03pb)
  3. **ZH associated production** (0.1~0.01pb)
- **Decay**
  - **m_H < 135 GeV**
    H → bb is dominant
  - **m_H > 135 GeV**
    H→ WW

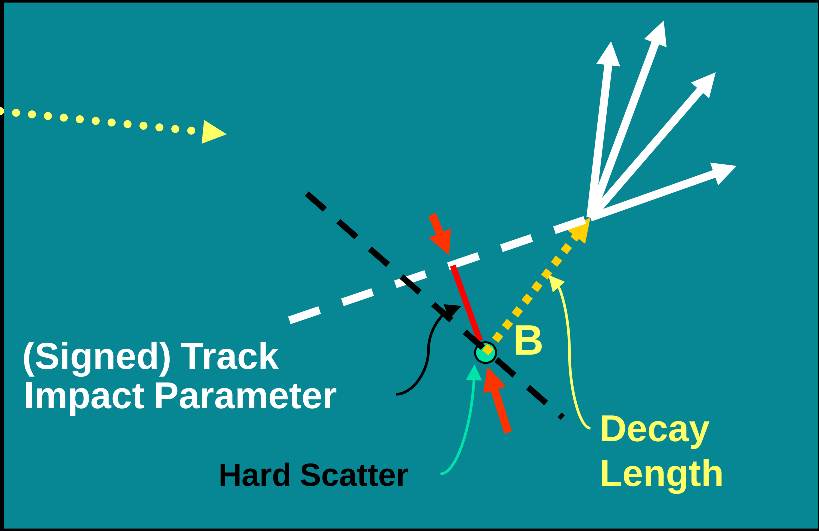
Analysis Strategy	**Background**
m_H < 135 GeV **WH/ZH + H→ bb**	**top, Wbb, Zbb**
m_H > 135 GeV **Gluon fusion + H→WW**	**WW, WZ** **Drell-Yann**

Low Mass SM Higgs Searches

- WH → $e(\mu)\nu + b\bar{b}$
- ZH → $(ee/\mu\mu)\nu\nu + b\bar{b}$
- Measurements rely on
  - b-tagging
  - Lepton identification + Missing-E_T resolution
  - Dijet mass resolution and light/b-jet calibration
    - Z → $b\bar{b}$
  - Understanding of backgrounds
    - W/Z + heavy-flavor/light jets

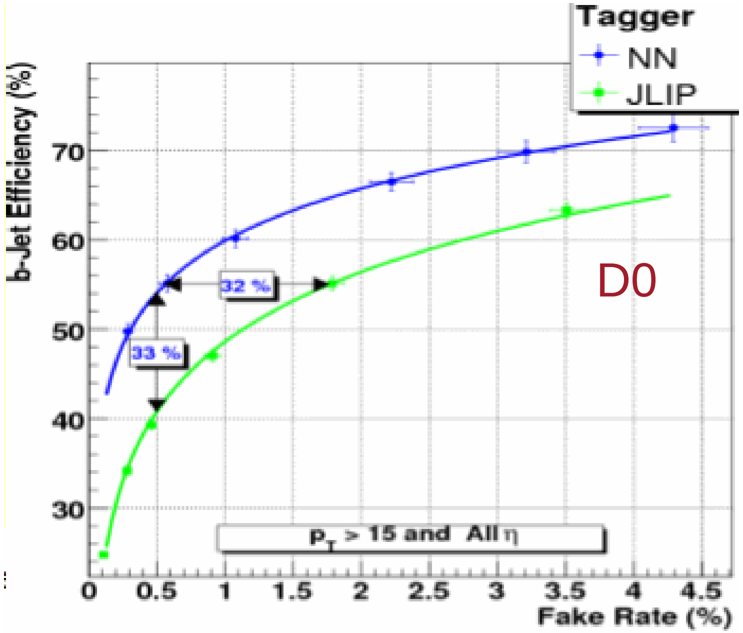
b-tagging (B lifetime (1.57±0.01 ps)

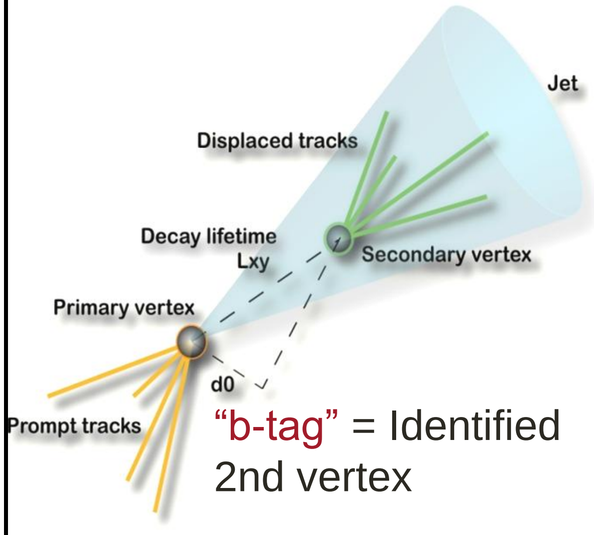
- Based on signed impact parameter resolution
  - Jet Lifetime Impact Parameter algorithm
- Based on decay length resolution
  - Secondary Vertex Algorithm



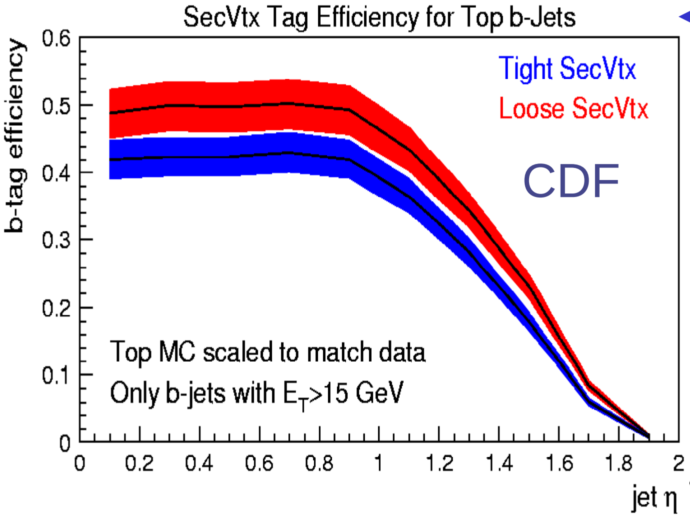
Identification of b-quarks (b-tagging)

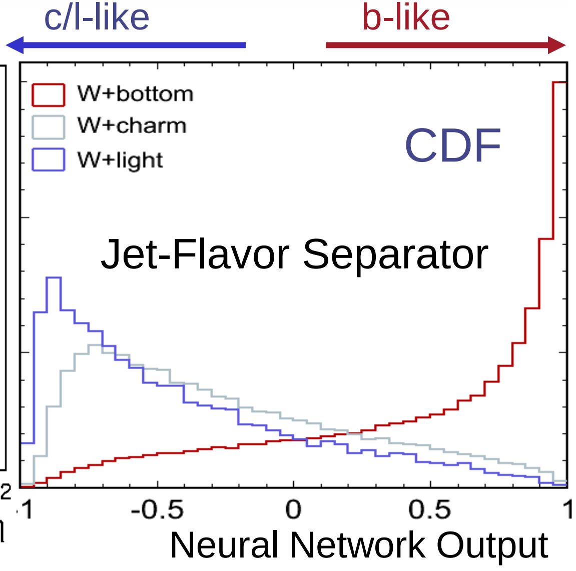
- Most sensitive channels have H→bb
- Silicon detectors used to find secondary vertices
- Efficiency ~40 - 70%
- Fake rate (mistags) typically 0.5 - 5%
- D0 uses Neural Network tagger based on b-lifetime information. Can use multiple operating points.
- CDF utilizes secondary vertex and Jet Probability algorithms + additional NN flavor separator
- Use either single tag or looser double tag





"b-tag" = Identified 2nd vertex





• The Challenge:

extract Higgs signal from a background 10 orders of magnitudes larger

1. Trigger

- High p_T e,μ triggers
- MET + Jets triggers
- Track + MET + Ecal τ-trigger

2. Reconstruct final state

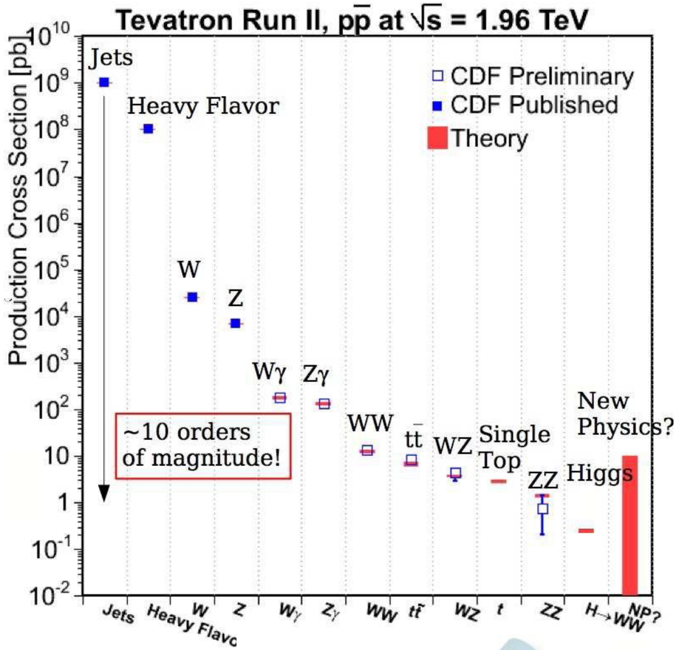
- Leptons ID (optimized on large *W/Zsamples)*
- Efficient b-jet tagging (NN tagger based on b-lifetime information)
- Good jet resolution
- MET reconstruction

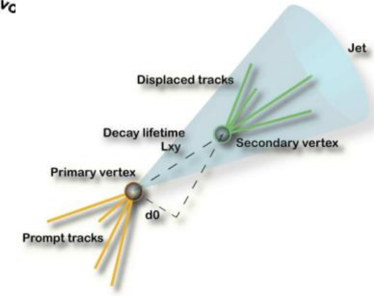
3. Background estimation is crucial

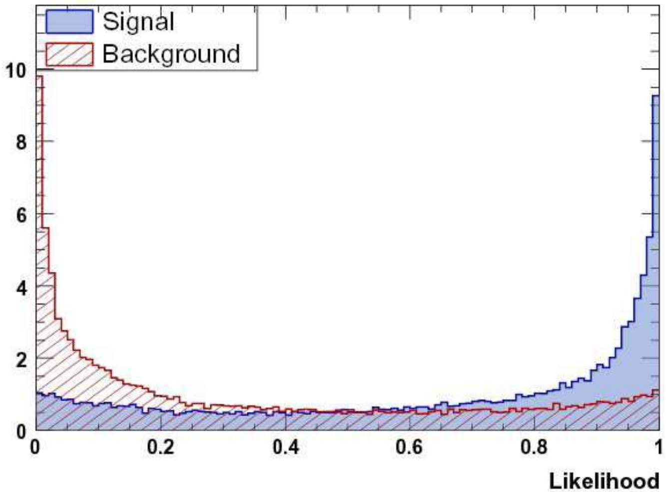
- MC predictions: W/Z+jets, diboson, top,...
- Data driven: mistags, QCD
- Exhaustive checks in control regions

4. Advance analysis techniques to separate signal from background

- Neural Network, Matrix Elements, Boosted Decision Trees,...



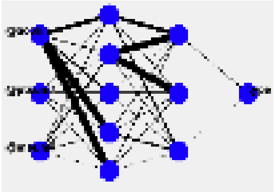




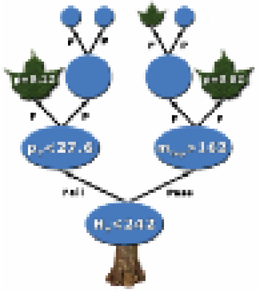
Tool: Multivariate Analysis (MVA)

In order to maximize sensitivity

- Neural Network (NN)
  - Well known technique.



- Boosted Decision Tree (BDT)
  - Relatively new.
  - BDT is fast
    → can handle more inputs.

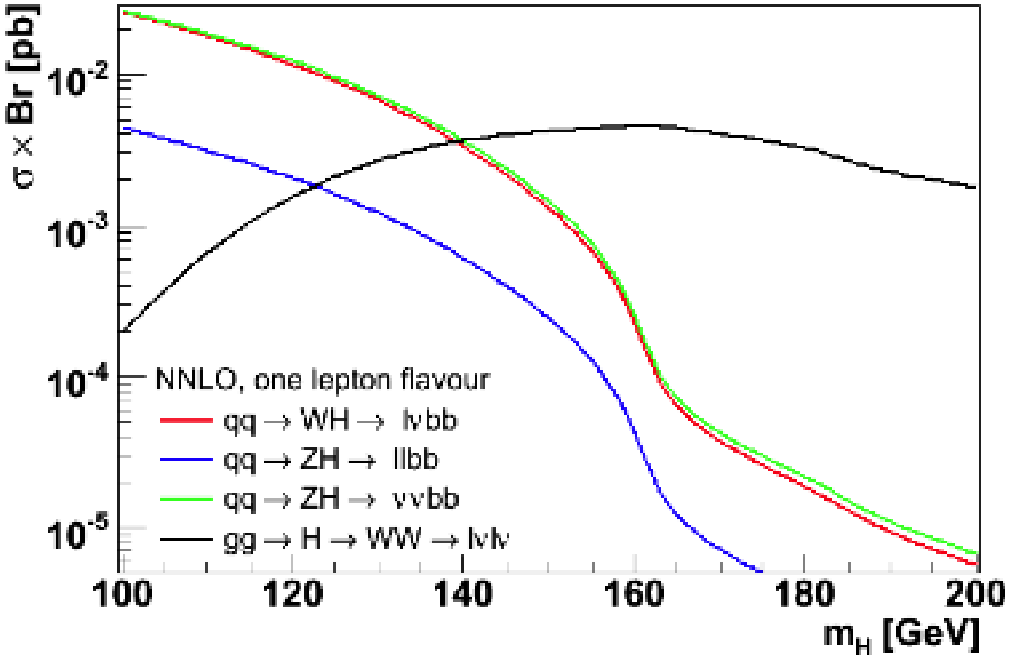


Major Inputs
- Dijet mass
- Pt of dijet
- Wpt, Zpt
- Sphericity
- q x η
- ΔRjj, Δφjj, Δηjj

- Matrix Element (ME)
  - Event probability can be obtained by integrating ME.
  - Input is 4 momentum vector for each objects.
  - Need huge CPU power.

These three approaches are often combined by Neural Net / BDT.

How to search higgs at low mass?



ZH→νν bb
MET+bb
Rich signal
0-lepton

WH→lν bb
l+MET+bb
Rich signal
1-lepton

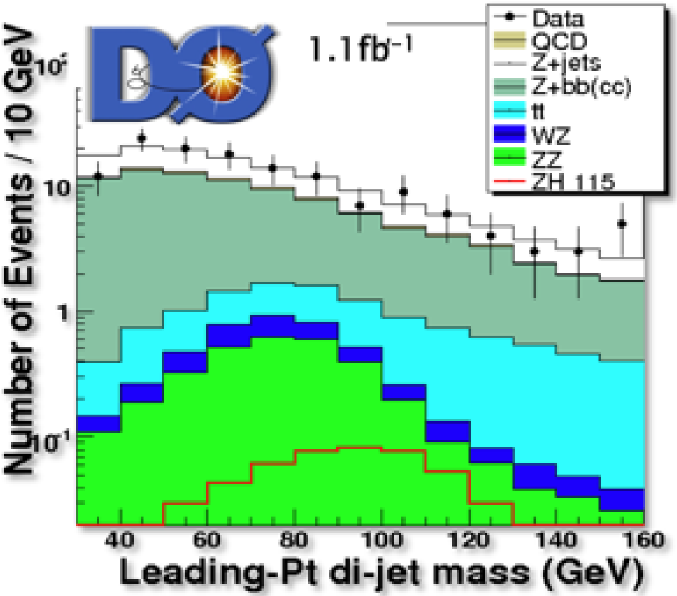
ZH→ll bb
2l(e/μ)+bb
less signal
2-lepton

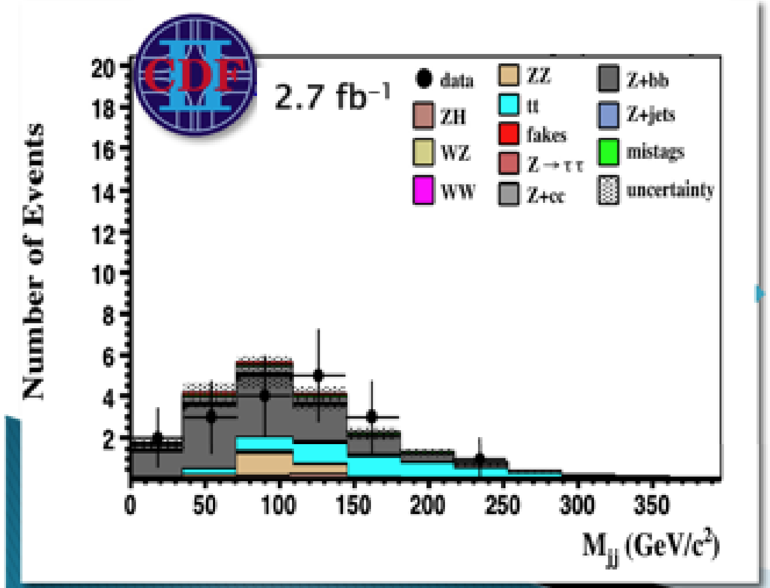
Multi-Jet (MJ) BG:
HIGH → LOW

Extension:
H→ γγ
VH→τ + jets
ttH→ttbb
Signal from
gg->H, VH, VBF

Two charged leptons: $ZH \to \ell^+\ell^- b\bar{b},\ \ell = e,\mu$

- Fully reconstructed final state
  - Two resonances: $H \to bb$ and $Z \to ll$
  - The dilepton mass cut $M_{ll} \approx M_Z$
- Dominant backgrounds:
  - Z+jets (irreducible Z+bb), top, dibosons
- Small σ×Br: ~1 event/fb^{-1}
  - Acceptance is crucial: employ loose *b*–tagging
  - Analyze events with at least one *b*–jet

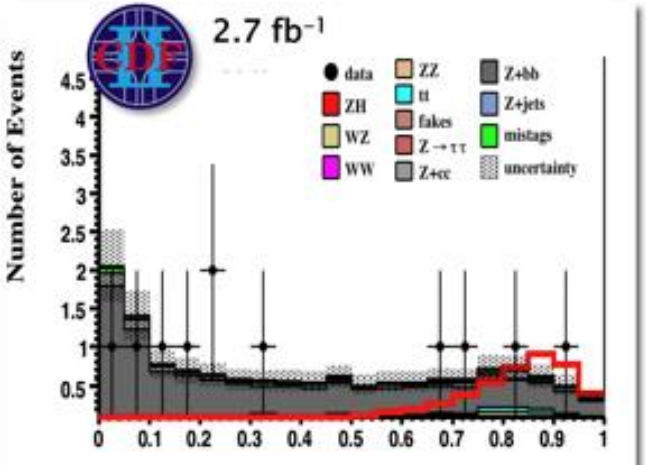




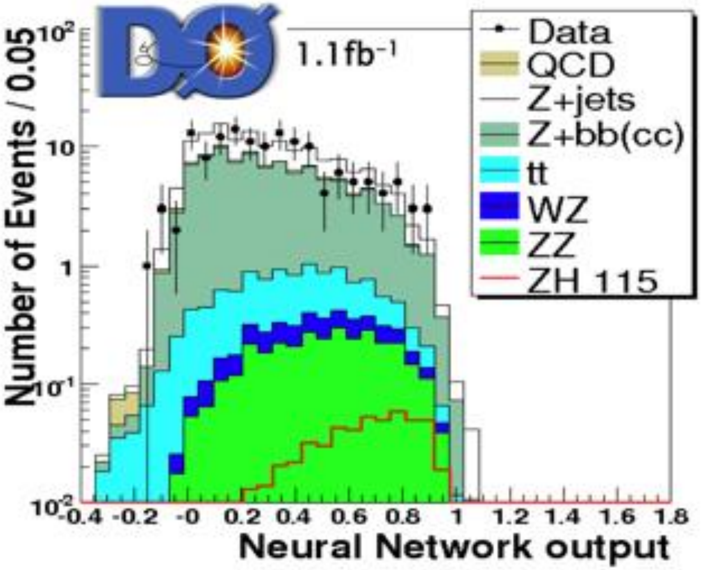
- Special techniques:
  - Correct jet E_T's using MET=> JER improves from 18% to 11%
  - Lepton coverage: stubless *μ*'s, forward *e*'s: improve limit by 10%

Two charged leptons: $ZH \to \ell^+\ell^- b\bar{b},\ \ell = e, \mu$

- Improve analysis sensitivity:
  - CDF: Matrix Element and 2D NN
  - DØ: NN for *ee* and BDT for *μμ* channels



ZH Neural Network

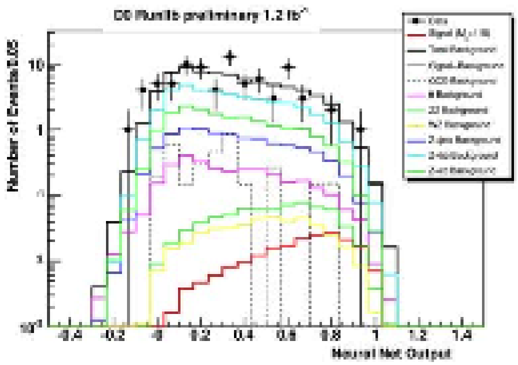


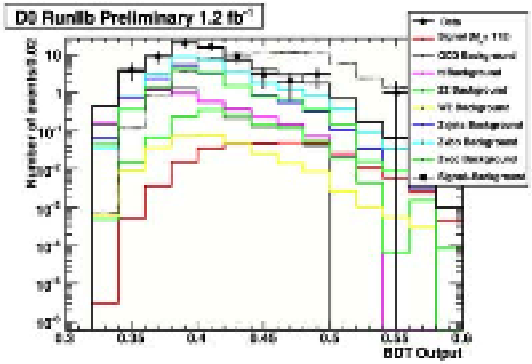
Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF ME (M_H=120)	2.1	1.4	15	14.2
CDF NN	2.7	2.1	9.9	7.1
DØ BDT	2.3	2.1	12.3	11.0

Limit/SM @ m_H =115 GeV/c^2

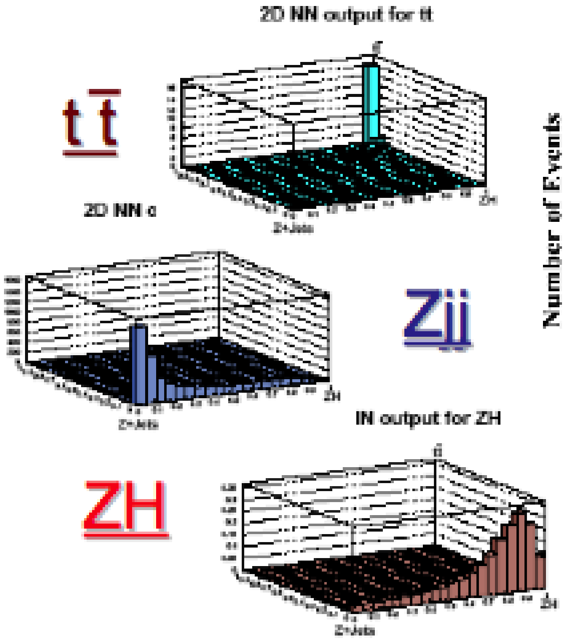
2 lepton: ZH→llbb MVA and result

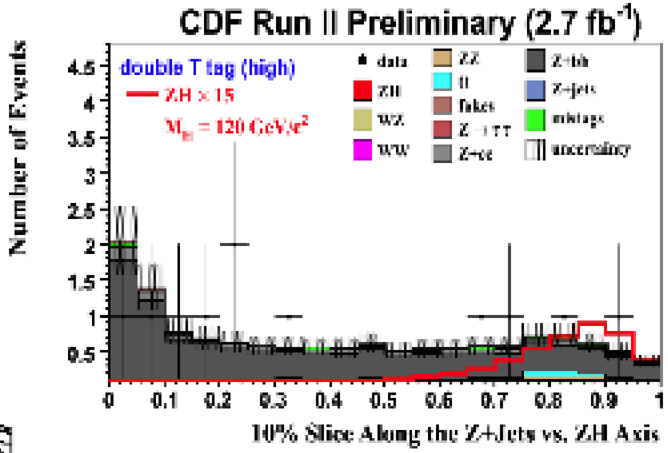
- DØ: NN, BDT(part of μ channel)





- CDF: 2 dimensional NN





Result:

No significant excess.

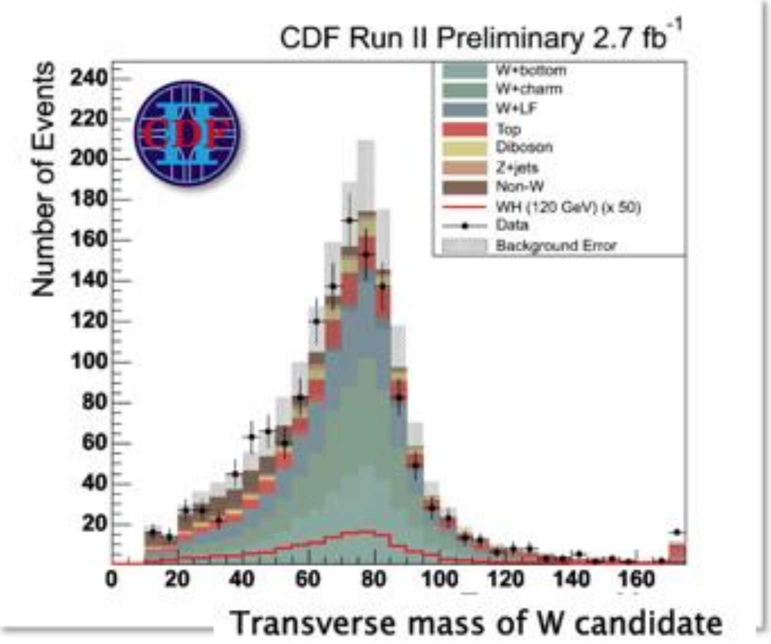
Limit / SM
@ m_H=115GeV

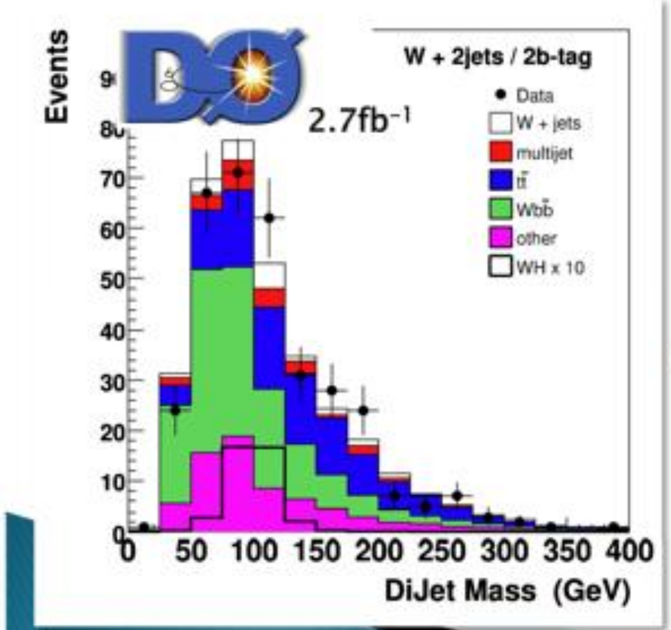
DØ 2.3 fb^{-1}:
exp : 12.3
obs : 11.0

CDF 2.7 fb^{-1} :
exp : 9.9
obs : 7.1

One charged lepton: $WH \to \ell\nu b\bar{b},\ \ell = e, \mu$

- *"Large"* $\sigma \times$Br, clean signature
  - Acceptance to about 3-4 events/fb^{-1}
  - High P_T leptons, MET and ≥2 jets
- Dominant backgrounds:
  - W+bb, top, diboson, QCD multi-jet

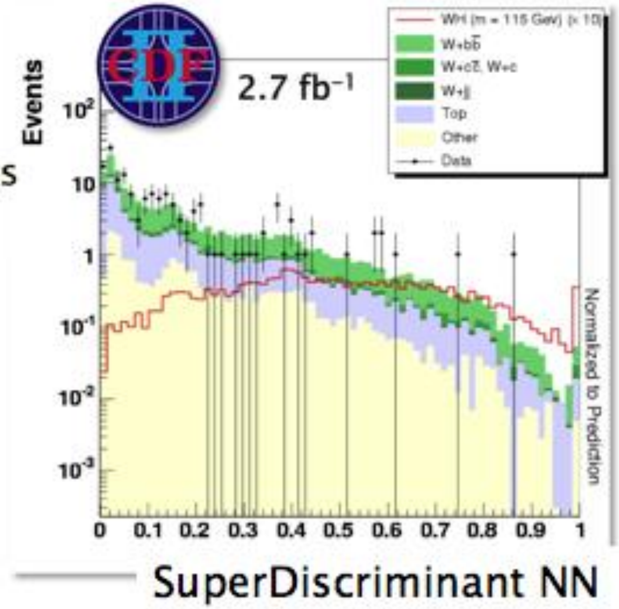


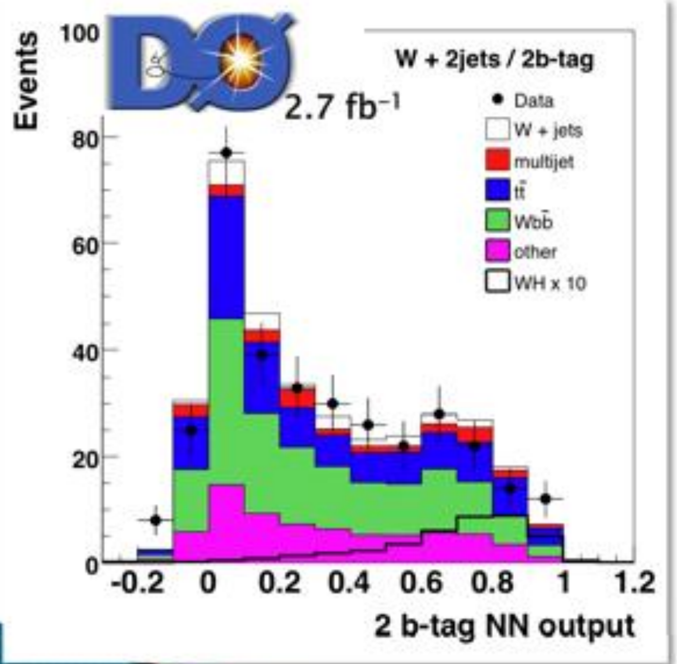


- Special techniques:
  - CDF/DØ: at least 1 b-tag, loose double-tag
  - CDF/DØ: ME to discriminate signal from bckg
  - CDF: loose muons, NN-based jet correction
  - DØ: forward electrons, events with 3 jets

One charged lepton: $WH \to \ell \nu b\bar{b},\ \ell = e, \mu$

- Improve analysis sensitivity:
  - CDF: BDT+NN → SuperDiscriminant using NEAT
  - DØ: NN for events with 2 jets, Dijet Mass for 3-jets



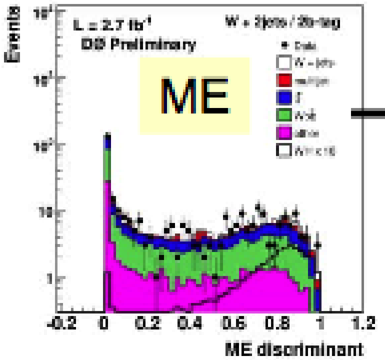


Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF NEAT	2.7	8.3	4.8	5.6
DØ NN	2.7	13.3	6.4	6.7

Limit/SM @ m_H =115 GeV/c^2

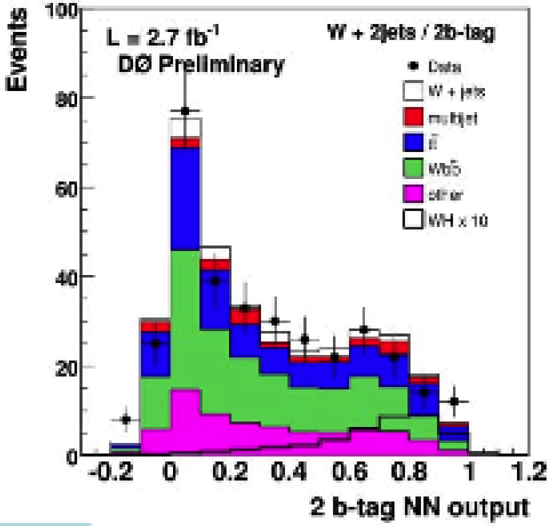
1 lepton: WH→lν bb result

DØ : NN with ME + 7 Var.

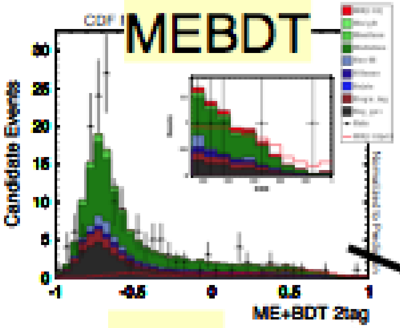


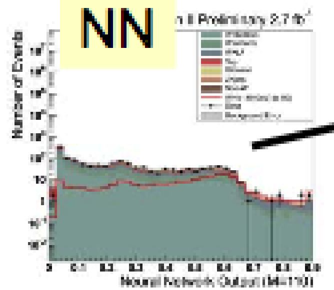
NN

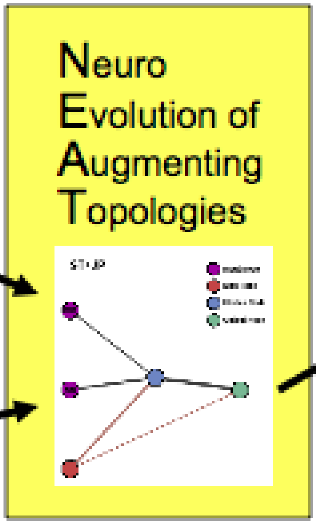
7 kin, var



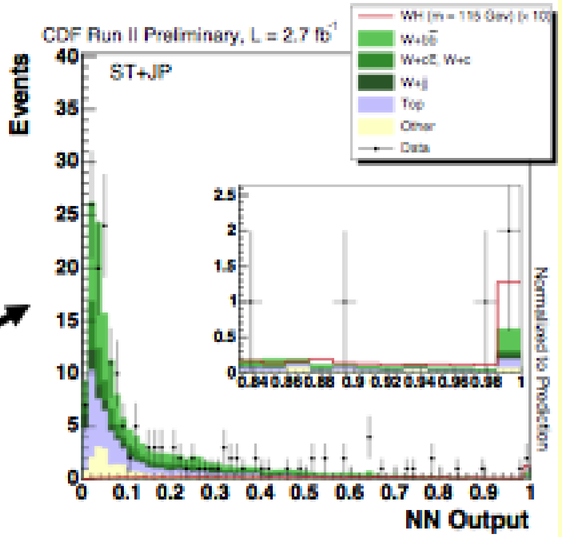
CDF : NEAT with MEBDT + NN







Neuro Evolution of Augmenting Topologies



Result:

No significant excess.

Limit / SM

@m_H=115GeV

DØ 2.7 fb^{-1}:

exp : 6.4

obs : 6.7

NEW

CDF 2.7 fb^{-1} :

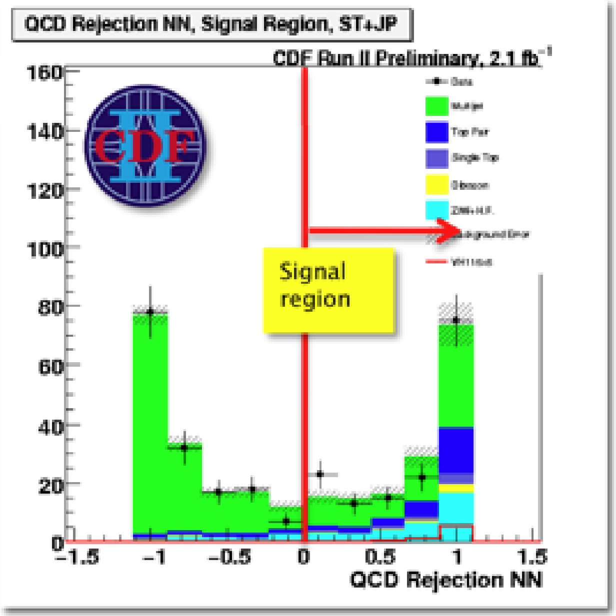
exp : 4.8

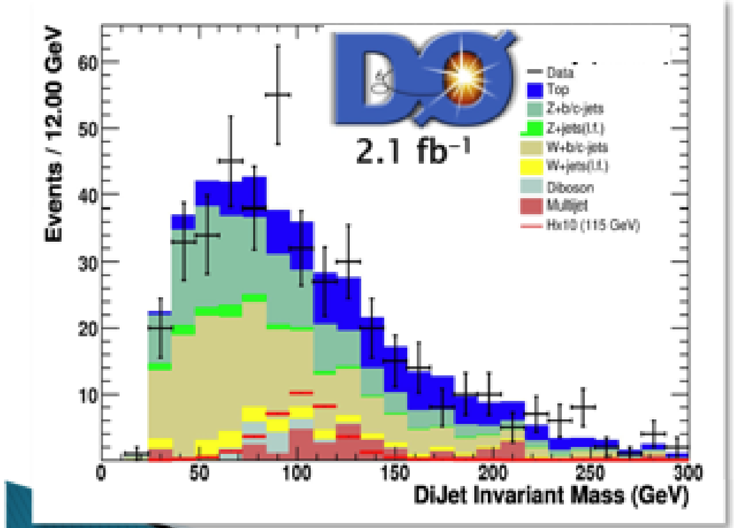
obs : 5.6

	exp	Obs
BDT	5.2	6.2
NN	5.8	5.2

Zero charged leptons: $VH \to \not{E}_T b\bar{b}$

- Large signal acceptance: $ZH \to \nu\nu b\bar{b}$ / $WH \to \not{\ell}\nu b\bar{b}$
    - Acceptance to about 3-4 events/fb^{-1}
    - Large MET and ≥2 jets
    - Information of W/Z missed: no strong constraints
- Dominant backgrounds:
    - QCD with fake MET, W/Z+jets, top, diboson

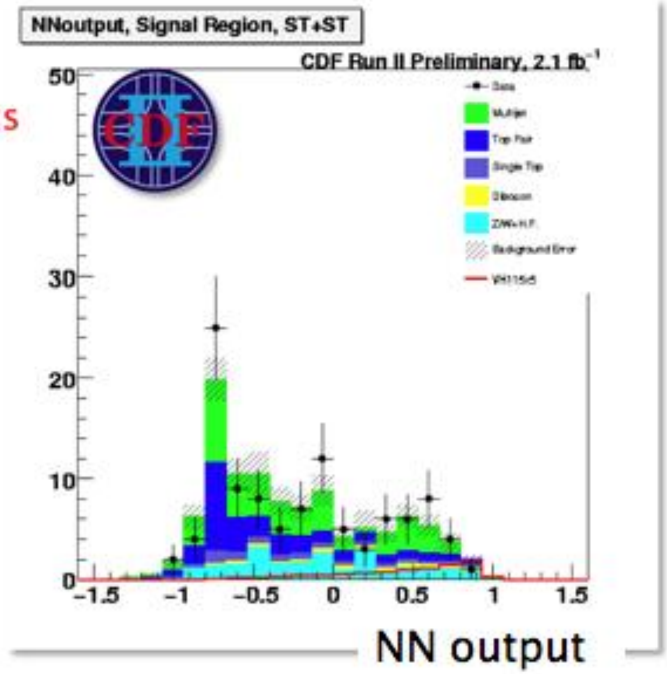


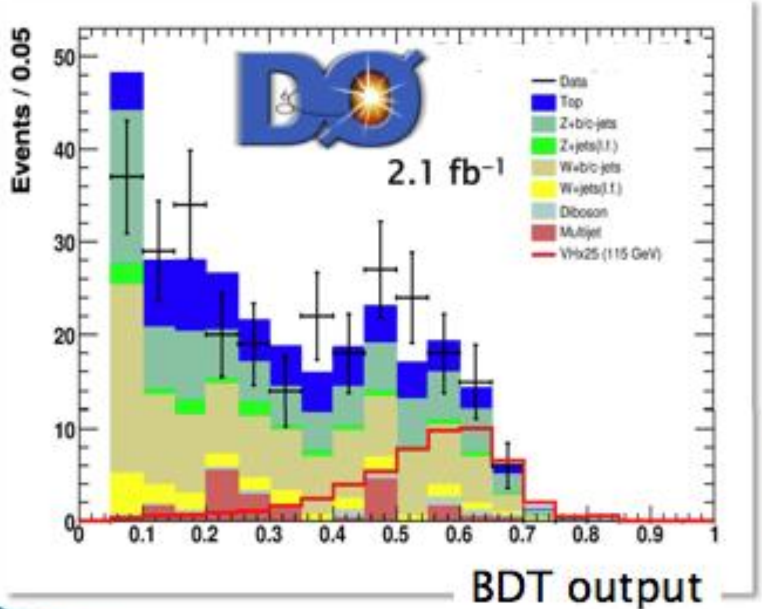


- Special techniques:
    - CDF/DØ: data-driven QCD model, track MP$_T$
    - CDF: at least 1 *b*-tag, 3 tagging channels, NN-based event selection *(QCD rejection NN)*, track-based jet corrections
    - CDF: accept $WH \to \tau\nu b\bar{b}$ with hadronic τ

Zero charged leptons: $VH \rightarrow \not{E}_T b\bar{b}$

- Improve analysis sensitivity:
  - CDF: NN with separate training for 2 and 3 jets
  - DØ: BDT for double tagged sample





Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF NN	2.1	7.5	5.6	6.9
DØ BDT	2.1	3.7	8.4	7.5

Limit/SM @ m_H =115 GeV/c^2

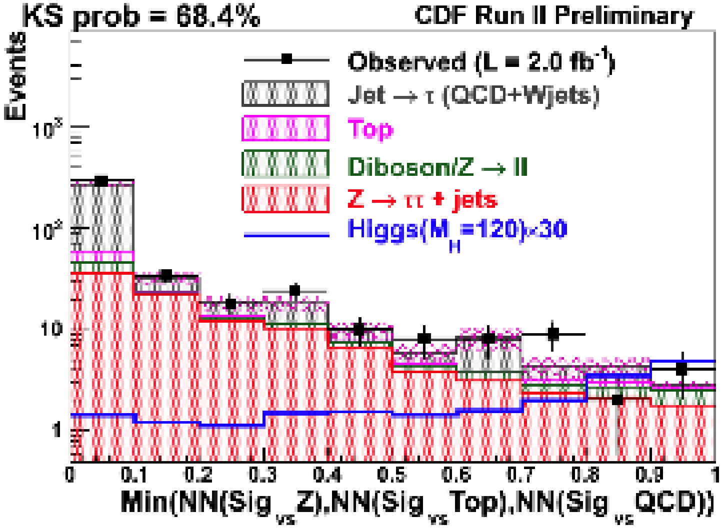
ggH, VH, VBF → tau + jj

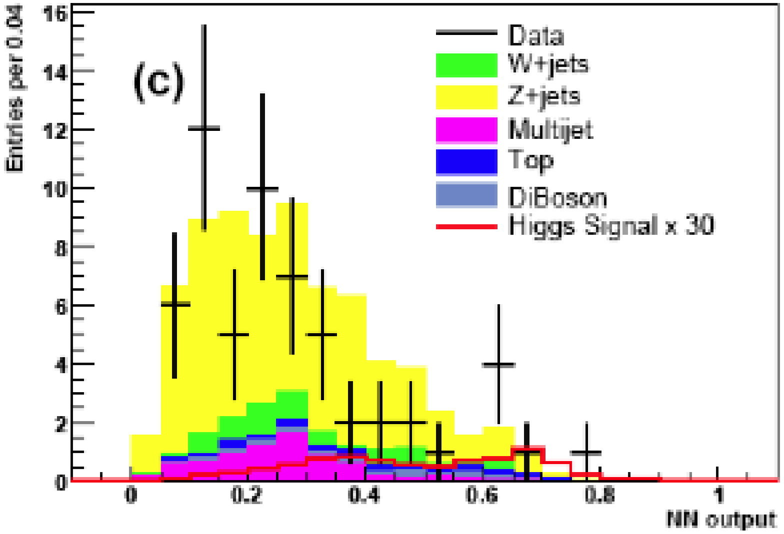
Search tau + jet final states from all production:
Gluon fusion, W/Z associated, Vector Boson Fusion production

CDF 2 fb^{-1}: $\tau\tau$**+ 2jet**
Train 3 NNets against 3 BG (tt, Z, MJ)

NEW

DØ 1 fb^{-1}:
tt+jj, Train NNets against each BG.
tν+bb: Use dijet mass





Limit / SM @ m_H = 115 GeV

$\tau\tau$ jj exp: 30 obs: 24

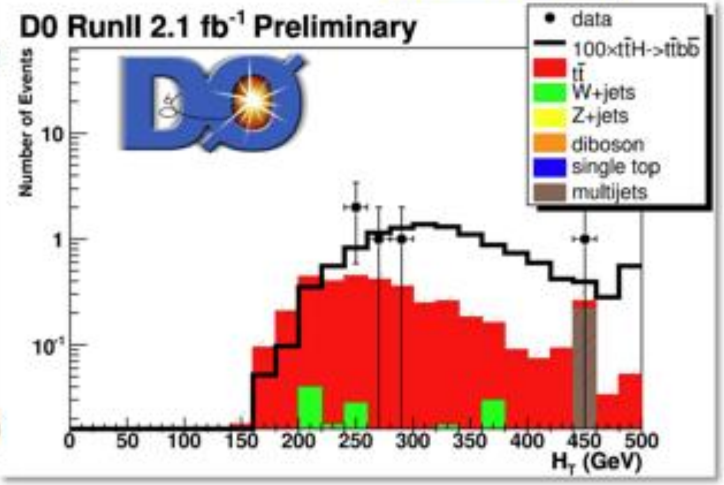
Limit / SM @ m_H = 115 GeV

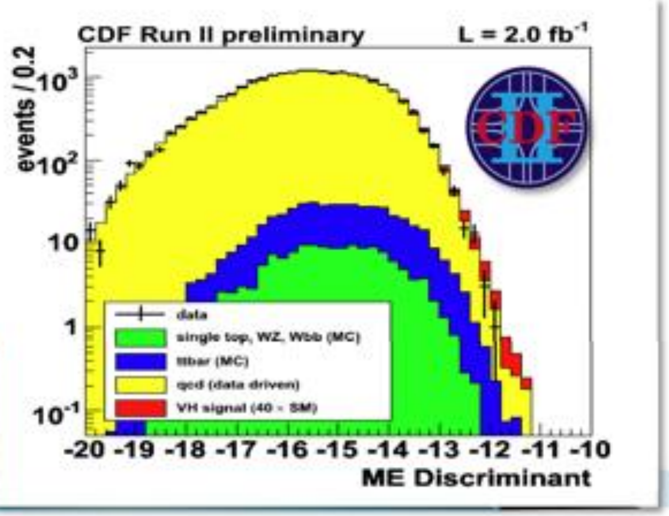
Final state	exp	Obs
τν bb	42.1	35.4
ττ jj	42.3	44.4
combine	27.6	27.3

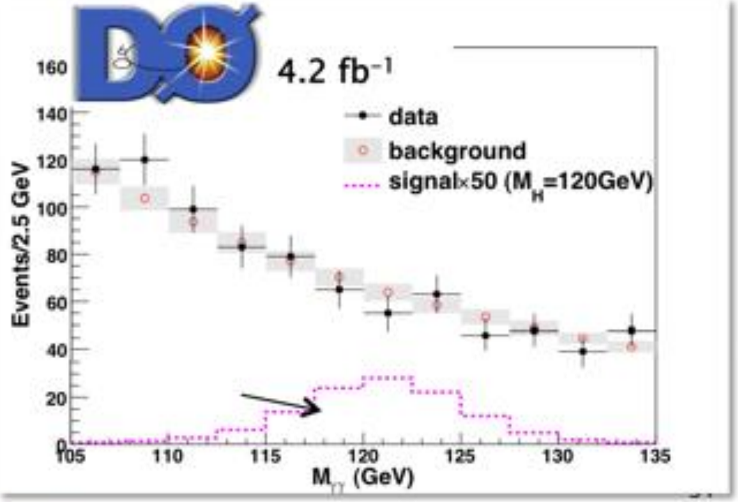
Additional channels

All limits on this page at MH=115

- DØ: ttH->*lνbbbbqq* (2.1fb^{-1})
  - Scan the distribution of H_T: scalar sum of je
  - 4 or 5 jets, 1-3 *b*-tagged jets
  - Exp (Obs) Limit: 45.3 (63.9)*SM
- DØ: H->γγ (4.2 fb^{-1})
  - Scan the Diphoton mass
  - Exp (Obs) Limit: 18.5 (15.8)*SM
- CDF: VH->*qqbb* (2.0fb^{-1})
  - Good signal acceptance: large BR(W/Z->qq)
  - Employ ME technique, 2 *b*-tagged jets
  - Exp (Obs) Limit 37 (38)*SM







H→ γγ : 4.2 fb-1 analysis from DØ

NEW

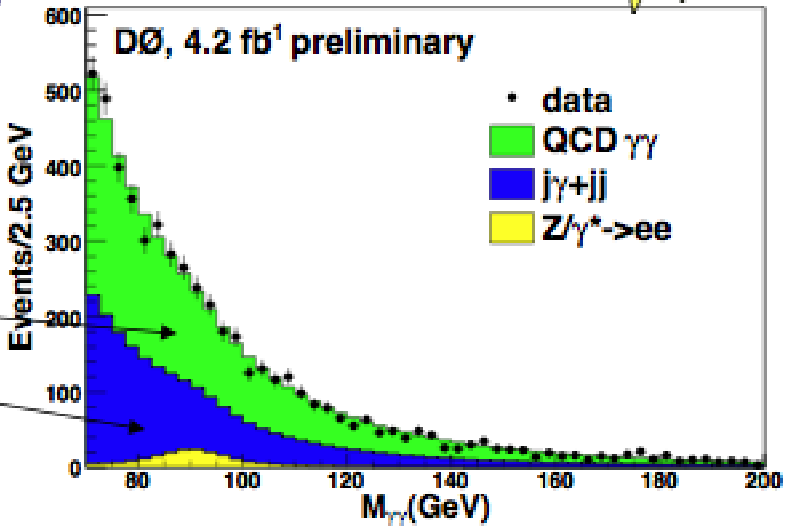
Gluon fusion, W/Z associated production, vector boson fusion production

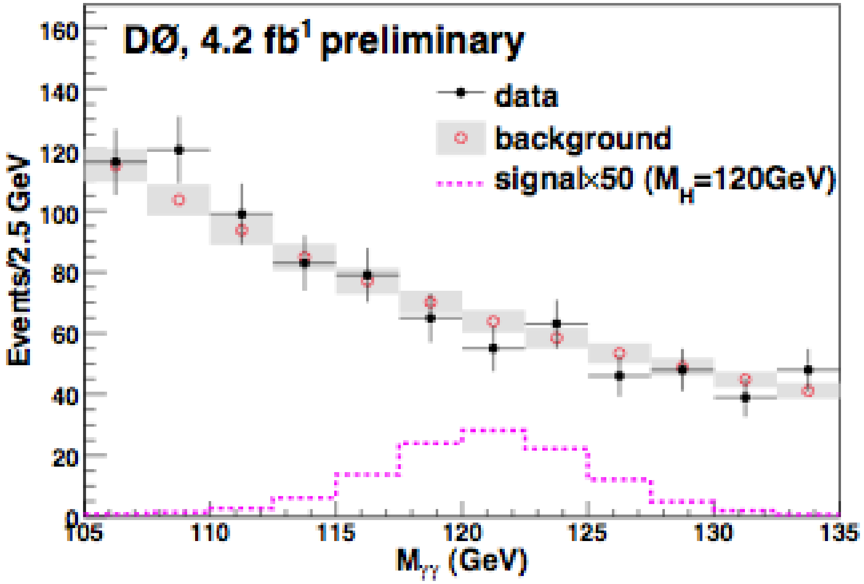
→ Compensate low Br(H→γγ) ~ 0.2%

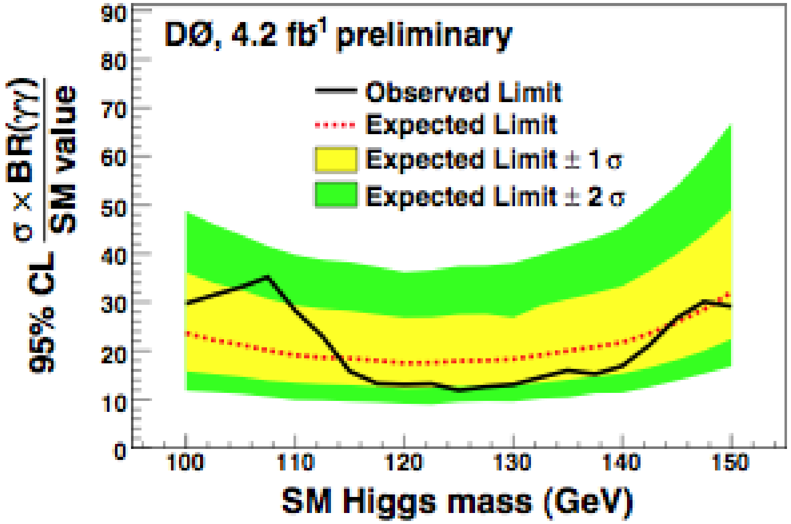
BG: i) QCD → γγ

ii) jet fake gamma.

iii) Drell-Yann







No significant excess is observed.

95% C.L. limit / SM @ m_H =120 GeV

exp: 17.5 obs: 13.1

Combination

- List of searches at low mass.

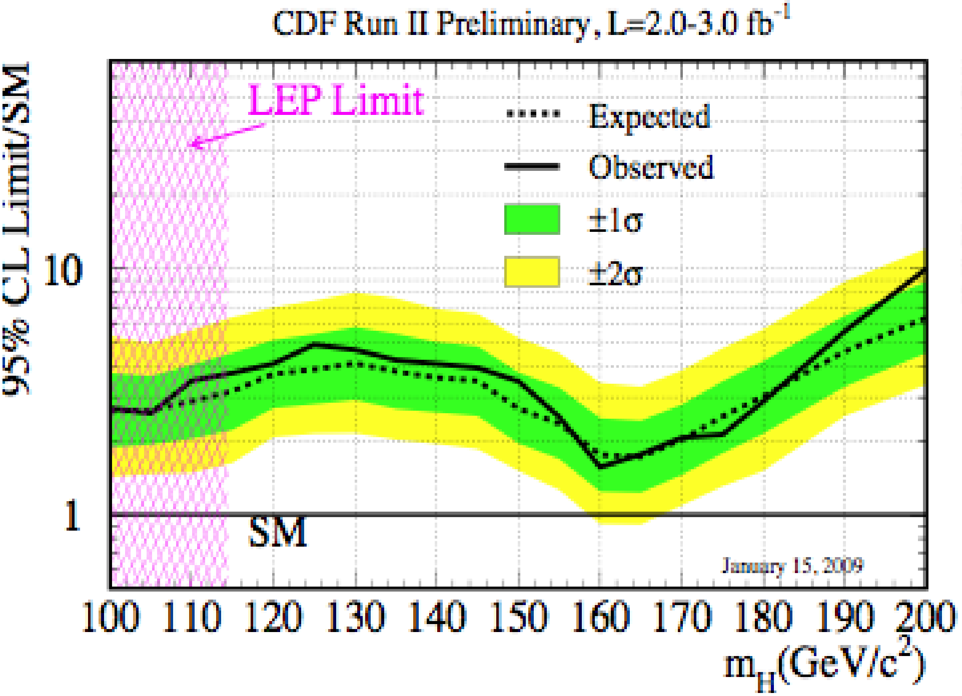
σ_H: NNLO
JHEP 0307, 028 (2008)

Production	Decay	CDF		DØ	
		Lumi	Limit/SM exp (obs)	Lumi	Limit/SM exp (obs)
WH	lν bb	2.7	4.8 (5.6)	2.7	6.4 (6.7)
ZH	ll bb	2.7	9.9 (7.1)	2.3	12.3 (11.0)
VH	νν bb	2.1	5.6 (6.9)	2.1	8.4 (7.5)
All	τ + jets	2.0	30 (24)	1.0	28 (27)
All	γγ	-----	-----	4.2	17.5 (13.1)
Not included					
WH	qqbb			-----	-----
ttH	lnjjbbbb	0.32	168	2.1	45(64)

Cross section limit / SM prediction

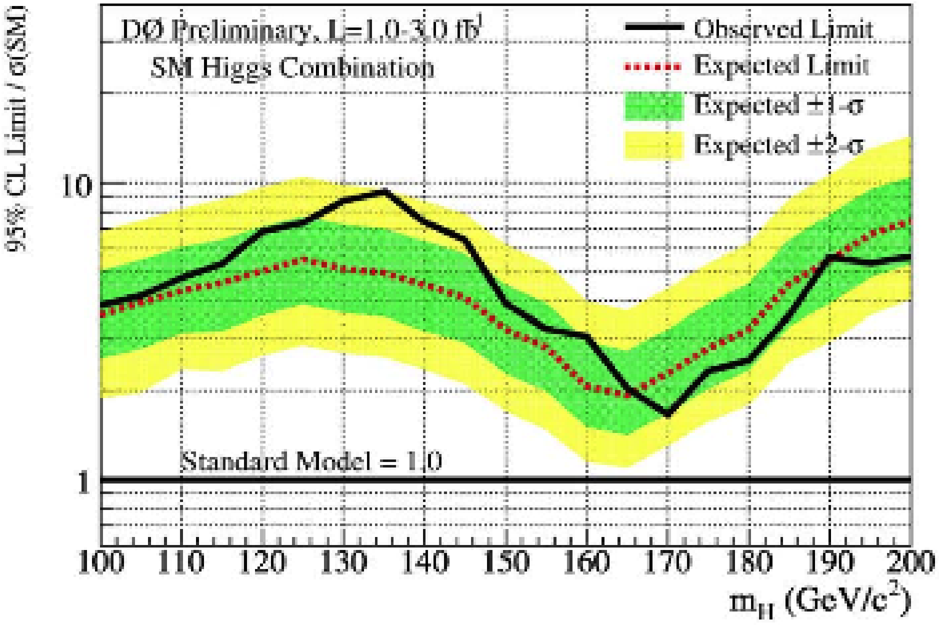
- Tevatron combination for Moriond 09 is not available yet. Will be available by end of conference.

CDF Combination (2009 Jan)



DØ Combination (2008 Aug)

Latest result is not included.



Limit / SM @ m_H = 115 GeV
CDF : exp 3.2 obs 3.8

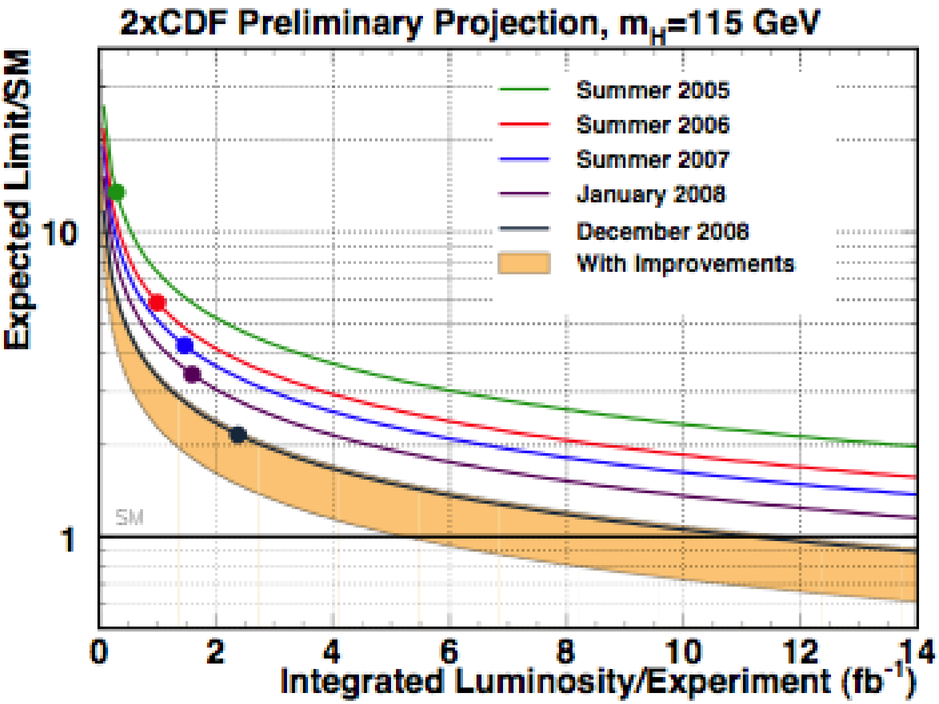
Limit / SM @ m_H = 115 GeV
DØ : exp 4.6 obs 5.3

Summary and prospect (Low mass Higgs)

- Higgs group working very hard in both CDF and DØ to find last missing piece of SM.
- No excess from BG expectation is observed yet.
- Cross section limit / SM @ 95 C.L. :

  CDF: 3.2 (3.8)   Dzero: 4.6 (5.3) @ m_H=115

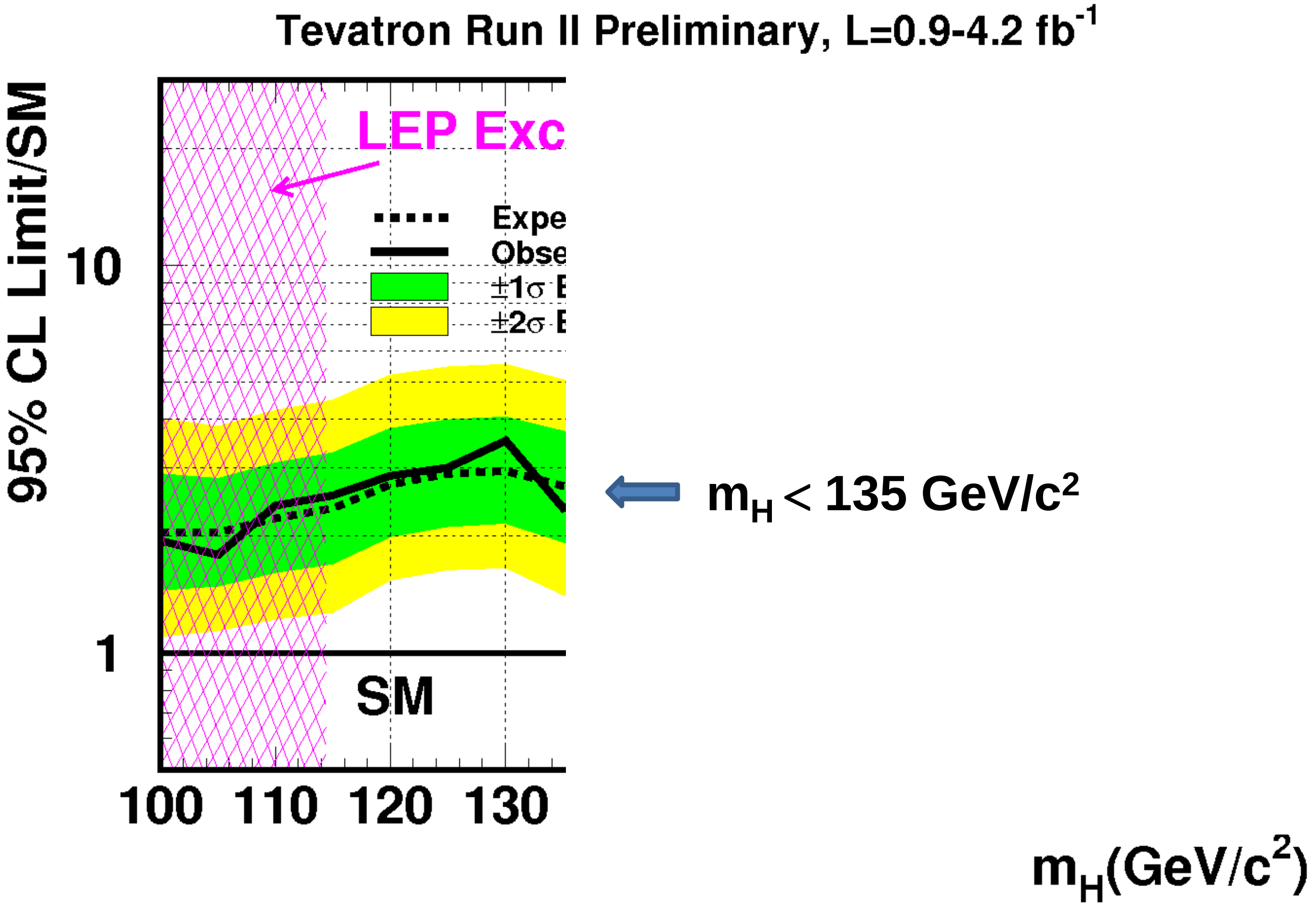
Combined result will be released end of Moriond EW!



Analyzable $\int \mathcal{L}\, dt$ will be reached more than 5 fb^{-1} very soon, This Summer!.

Exciting searches are on going! ***Stay Turned !***

Tevatron CDF & D0 combined (March 2009)



$m_H < 135$ GeV/c^2

Conclusions for low mass Higgs at TEVATRON

- Higgs physics at the Tevatron is getting exciting!

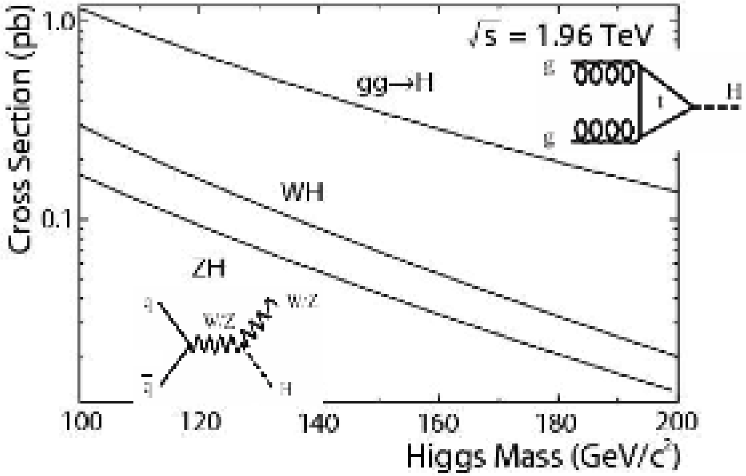
- Low mass region has large backgrounds, but can be suppressed by multi-variant techniques and understood in control regions

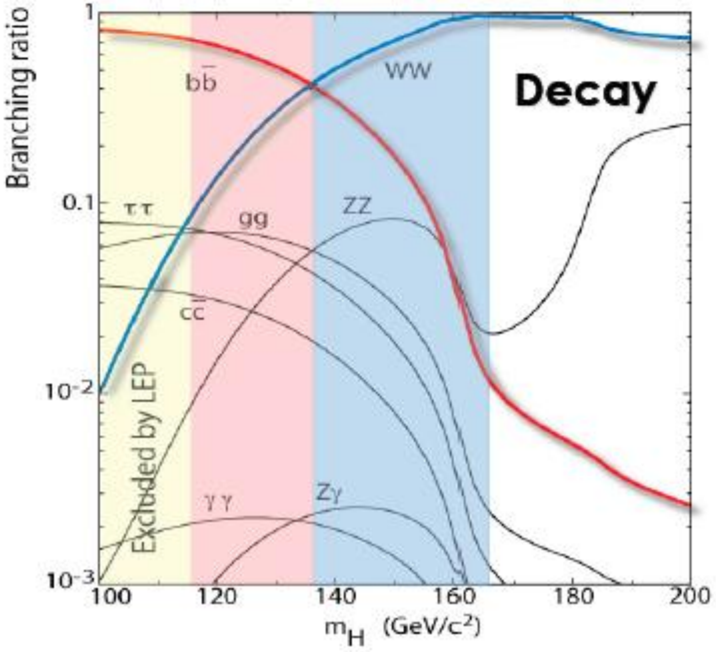
- Additional improvements actively in progress
  - Further extending signal acceptance for leptons and b tagging
  - Improved jet resolution
  - Extended b-tagging and flavour separators

- Expect 2-3 times current analyzed lumi (more if we run in 2010)

- Details on each analysis is available at:
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg/hdg.html
  - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

SM Higgs search at Tevatron





- **Production**
  1. **Gluon fusion** (0.8 ~ 0.2 pb)
  2. **WH associated production** (0.2~0.03pb)
  3. **ZH associated production** (0.1~0.01pb)
- **Decay**
  - **m_H < 135 GeV H → bb is dominant**
  - **m_H > 135 GeV H→ WW**

Analysis Strategy	**Background**
m_H < 135 GeV **WH/ZH + H→ bb**	**top, Wbb, Zbb**
m_H > 135 GeV **Gluon fusion + H→WW**	**WW, WZ** **Drell-Yann**

High Mass

$gg \rightarrow H \rightarrow WW^{(*)} \rightarrow ll'\nu\nu$ (l,l'=e,mu)

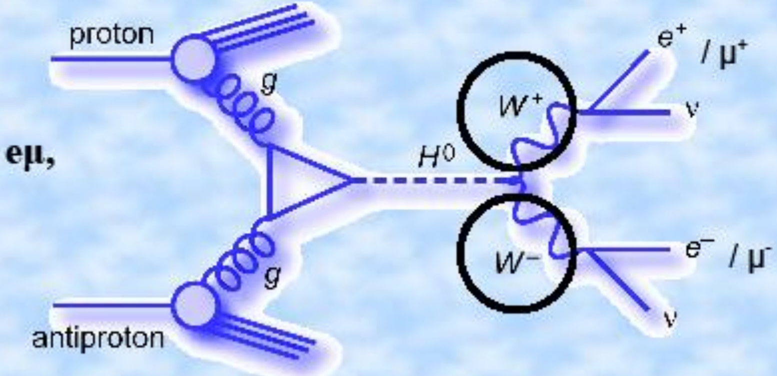
✔ Most sensitive Higgs search at the Tevatron

✔ **Signature:** 2 high p_T leptons + MET.

✔ Leptons in same directions due to spin correlation.

✔ Different background composition: *WW*, Drell-Yan, *tt*...

Final states: e^+e^-, $e\mu$, or $\mu^+\mu^-$ and 2 ν.



✔ There are several production mechanisms besides gluon fusion:
WH → WWW, ZH → WWW, V.B.F H → WW

✔ New dedicated analyses in different 0, 1, 2 jet bins.

✔ Analyses optimized for each jet bin.

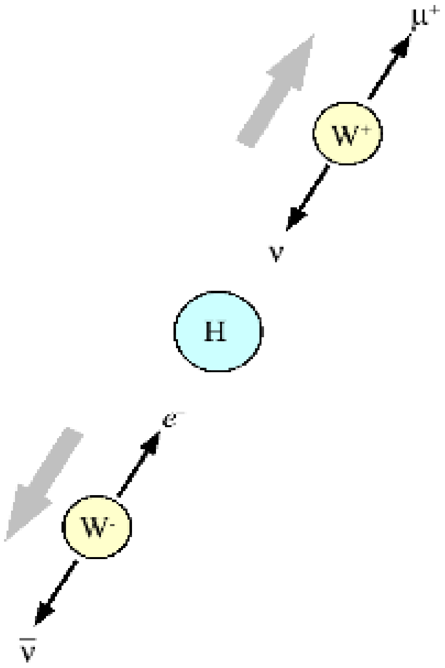
Both experiments approaching SM sensitivity

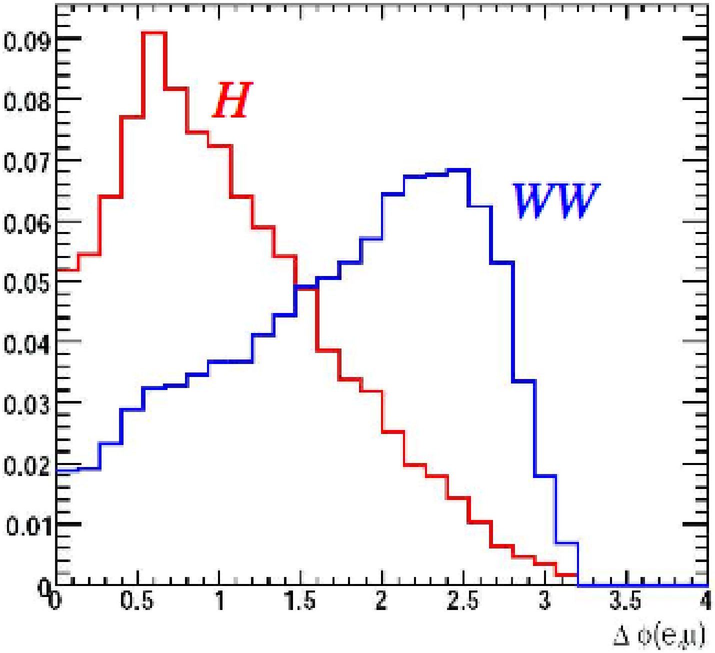
$H \rightarrow WW$

- Most sensitive Higgs channel at the Tevatron.
  - Highest sensitivity around M_H=160 GeV.
- Signature two high p_T leptons (ℓ=e or μ) and missing E_T.
- Backgrounds: WW, WZ, ZZ, tt, W+γ/jets, $Z\rightarrow\ell\ell$, $Z\rightarrow\tau\tau$, QCD.
- Strategies.
  - Good lepton id and missing E_T resolution.
  - WW is a fundamental physics background, and one of the largest backgrounds. Spin correlation ($\Delta\phi_{\ell\ell}$)is the best single variable for discriminating H and WW.
  - All subchannels and both experiments make use of advanced multivariate techniques to get best possible signal / background discrimination.

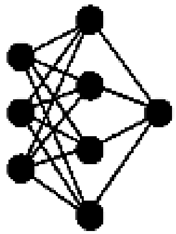
Spin Correlation in $H \rightarrow WW$

- Leptons from $H \rightarrow WW \rightarrow \ell\ell$ tend to be emitted in the same direction (i.e. small $\Delta\phi(\ell,\ell)$).

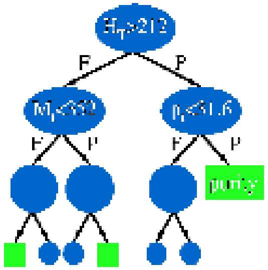




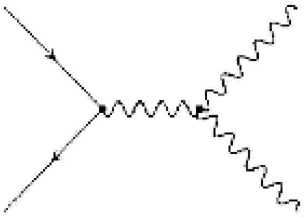
Multivariate Analysis Techniques



- Neural Networks (NN).
  - Works well. Time-tested – have been used successfully for many years.



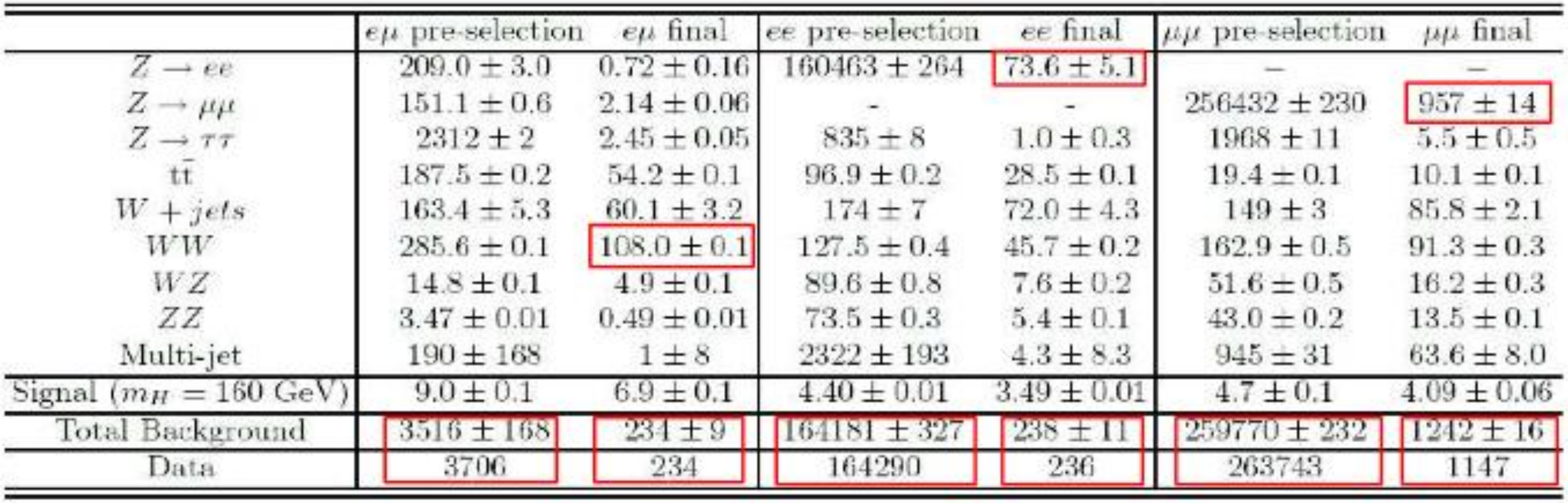
- Boosted Decision Trees (BDT).
  - Relatively recent. Popularity has grown enormously recently.



- Matrix Element (ME).
  - Highly efficient for specific signals / backgrounds.
  - Computationally costly.
  - Can be used as input to other techniques.

$H \to WW$ Event Selection

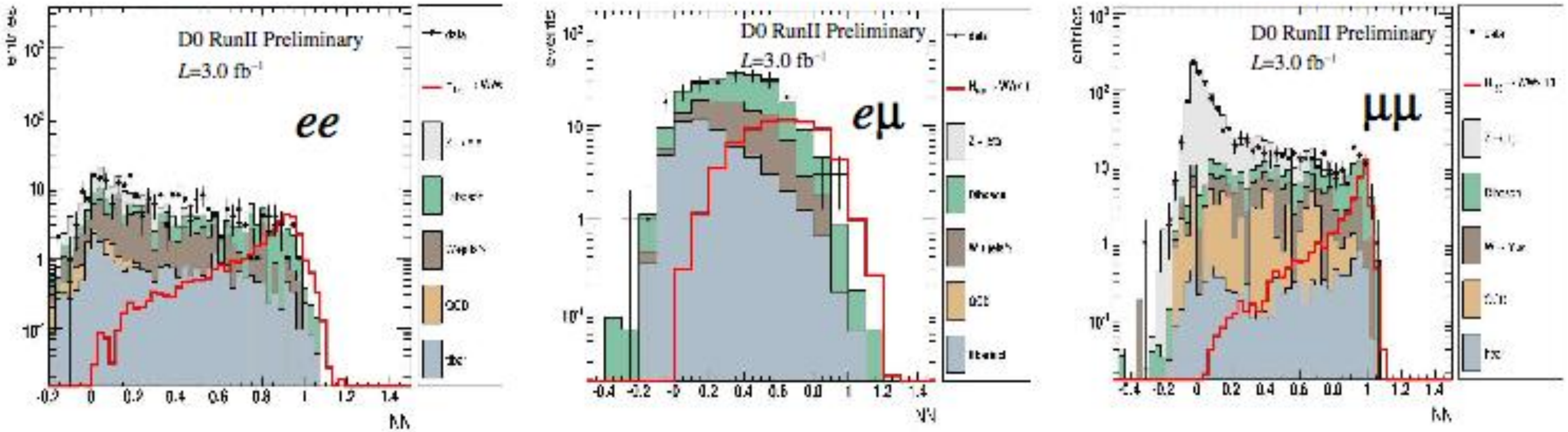
	ee	$e\mu$	$\mu\mu$
Leptons (preselection)	$p_T(\mu) > 10$ GeV, $p_T(e) > 15$ GeV, $M_{\ell\ell} > 15$ GeV		
$\not{E}_T$ (GeV)	>20	>20	>20
$\not{E}_T^{\text{Scaled}}$	>7	>6	>5
$M_T^{\min}(\ell, \not{E}_T)$ (GeV)	>20	>30	>20
$\Delta\phi(\ell,\ell)$	<2.0	<2.0	<2.5



	$e\mu$ pre-selection	$e\mu$ final	ee pre-selection	ee final	$\mu\mu$ pre-selection	$\mu\mu$ final
$Z \to ee$	209.0 ± 3.0	0.72 ± 0.16	160463 ± 264	73.6 ± 5.1	–	–
$Z \to \mu\mu$	151.1 ± 0.6	2.14 ± 0.06	-	-	256432 ± 230	957 ± 14
$Z \to \tau\tau$	2312 ± 2	2.45 ± 0.05	835 ± 8	1.0 ± 0.3	1968 ± 11	5.5 ± 0.5
$t\bar{t}$	187.5 ± 0.2	54.2 ± 0.1	96.9 ± 0.2	28.5 ± 0.1	19.4 ± 0.1	10.1 ± 0.1
$W + jets$	163.4 ± 5.3	60.1 ± 3.2	174 ± 7	72.0 ± 4.3	149 ± 3	85.8 ± 2.1
WW	285.6 ± 0.1	108.0 ± 0.1	127.5 ± 0.4	45.7 ± 0.2	162.9 ± 0.5	91.3 ± 0.3
WZ	14.8 ± 0.1	4.9 ± 0.1	89.6 ± 0.8	7.6 ± 0.2	51.6 ± 0.5	16.2 ± 0.3
ZZ	3.47 ± 0.01	0.49 ± 0.01	73.5 ± 0.3	5.4 ± 0.1	43.0 ± 0.2	13.5 ± 0.1
Multi-jet	190 ± 168	1 ± 8	2322 ± 193	4.3 ± 8.3	945 ± 31	63.6 ± 8.0
Signal ($m_H = 160$ GeV)	9.0 ± 0.1	6.9 ± 0.1	4.40 ± 0.01	3.49 ± 0.01	4.7 ± 0.1	4.09 ± 0.06
Total Background	3516 ± 168	234 ± 9	164181 ± 327	238 ± 11	259770 ± 232	1242 ± 16
Data	3706	234	164290	236	263743	1147

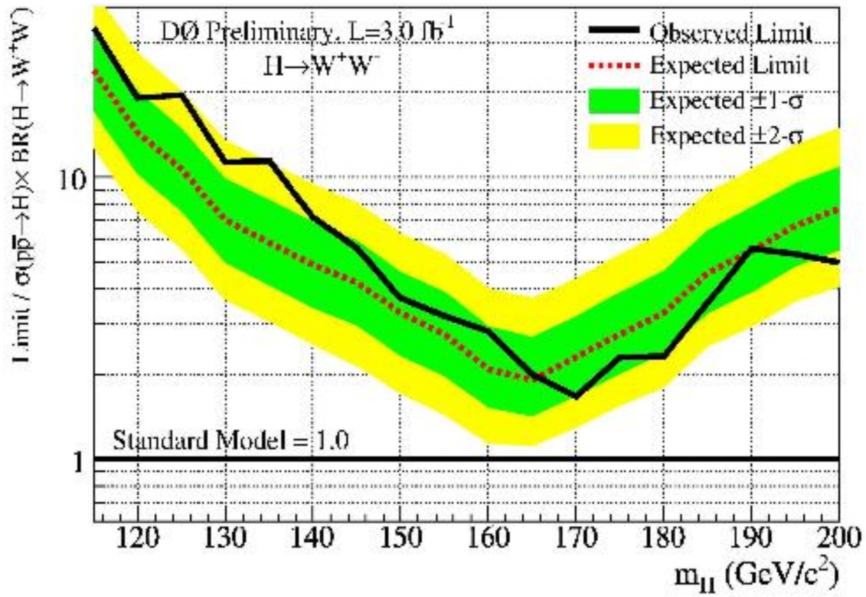
$H \rightarrow WW$ NN Analysis

- Neural network analysis makes use of 14 input variables.



$H \to WW$ Result

- Upper limit on $\sigma \times BR$ set using entire NN output distribution for all channels using modified frequentist method (CLs method).



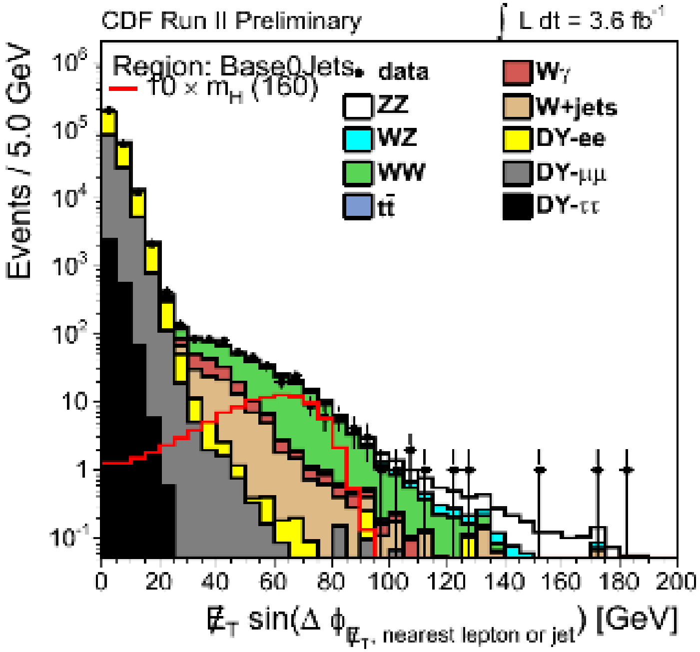
Expected limit is 2.1 times SM at M_H=160 GeV

$H \to WW$ Event Selection

	ee	$e\mu$	$\mu\mu$
Leptons	$p_{T1} > 20$ GeV, $p_{T2} > 10$ GeV, $M_{\ell\ell} > 16$ GeV		
$\not\!\!E_{T\mathrm{spec}}$ (GeV)	>25	>15	>25

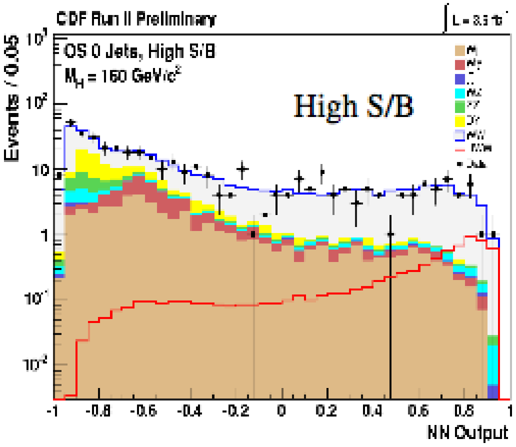
$$\not\!\!E_{T\mathrm{spec}} = \not\!\!E_T \sin\{\min[\pi/2, \Delta\phi(E_T, \ell j)]\}$$

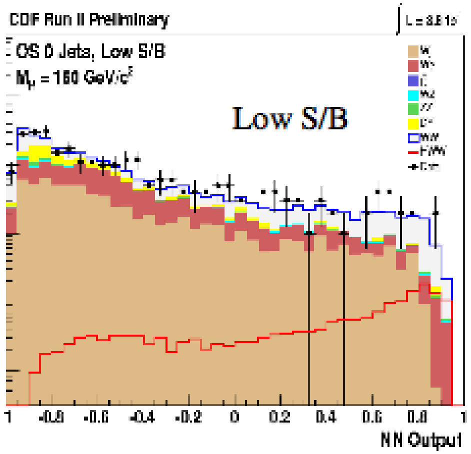
- Separate NN analysis for 0, 1, and ≥2 jets.
- 1 and 2 jets includes VBF and VH contributions to signal.
- Also separate NN analysis for high and low S/B events based on lepton quality for 0 and 1 jets.

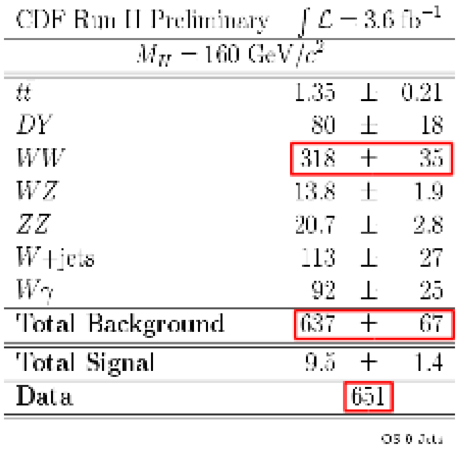


H→*WW* 0 jets NN Analysis

- Neural network analysis makes use of 5 input variables, including $\Delta\phi_{\ell\ell}$ and *H* vs. *WW* matrix element likelihood ratio (LRHWW).
- Separate NN for high and low S/B lepton id.







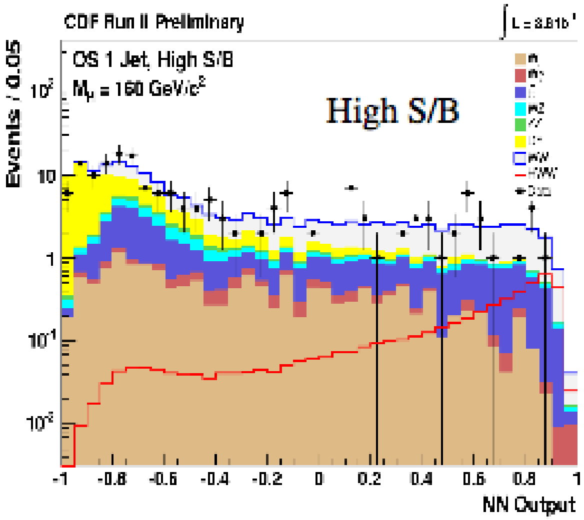
CDF Run II Preliminary $\int \mathcal{L} = 3.6\ \mathrm{fb}^{-1}$

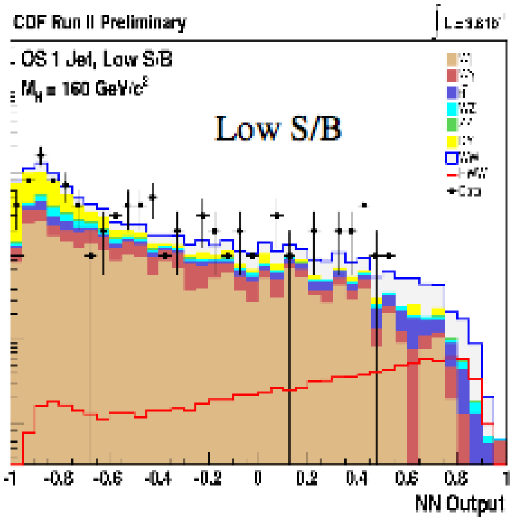
$M_H = 160\ \mathrm{GeV}/c^2$			
$t\bar{t}$	1.35	±	0.21
DY	80	±	18
WW	318	±	35
WZ	13.8	±	1.9
ZZ	20.7	±	2.8
W+jets	113	±	27
$W\gamma$	92	±	25
Total Background	637	±	67
Total Signal	9.5	±	1.4
Data		651	

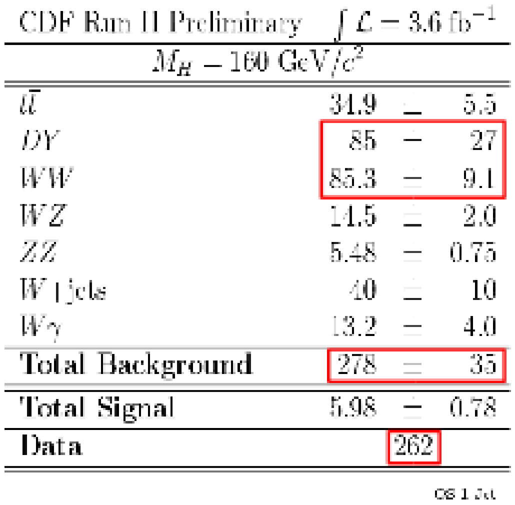
OS 0 Jets

$H \to WW$ 1 jets NN Analysis

- Neural network analysis makes use of 8 input variables (LRHWW not included for >0 jets).
- Separate NN for high and low S/B lepton id.







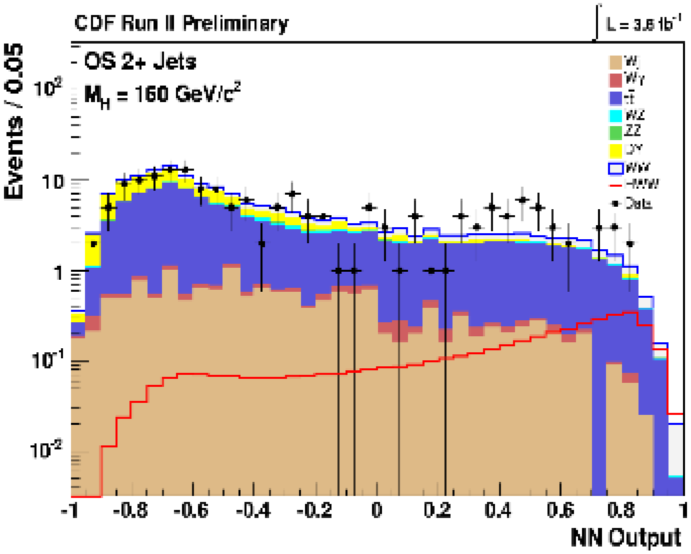
CDF Run II Preliminary $\int \mathcal{L} = 3.6\ \mathrm{fb}^{-1}$

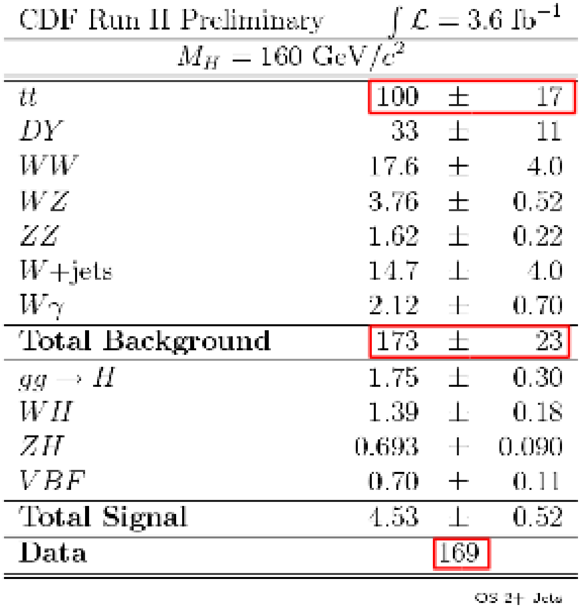
$M_H = 160\ \mathrm{GeV}/c^2$			
$t\bar{t}$	34.9	±	5.5
DY	85	±	27
WW	85.3	±	9.1
WZ	14.5	±	2.0
ZZ	5.48	±	0.75
W+jets	40	±	10
$W\gamma$	13.2	±	4.0
Total Background	278	±	35
Total Signal	5.98	±	0.78
Data	262		

OS 1 Jet

H→*WW* 2+ jets NN Analysis

- Neural network analysis makes use of 8 input variables.
- High and low S/B lepton id not used for ≥2 jets.



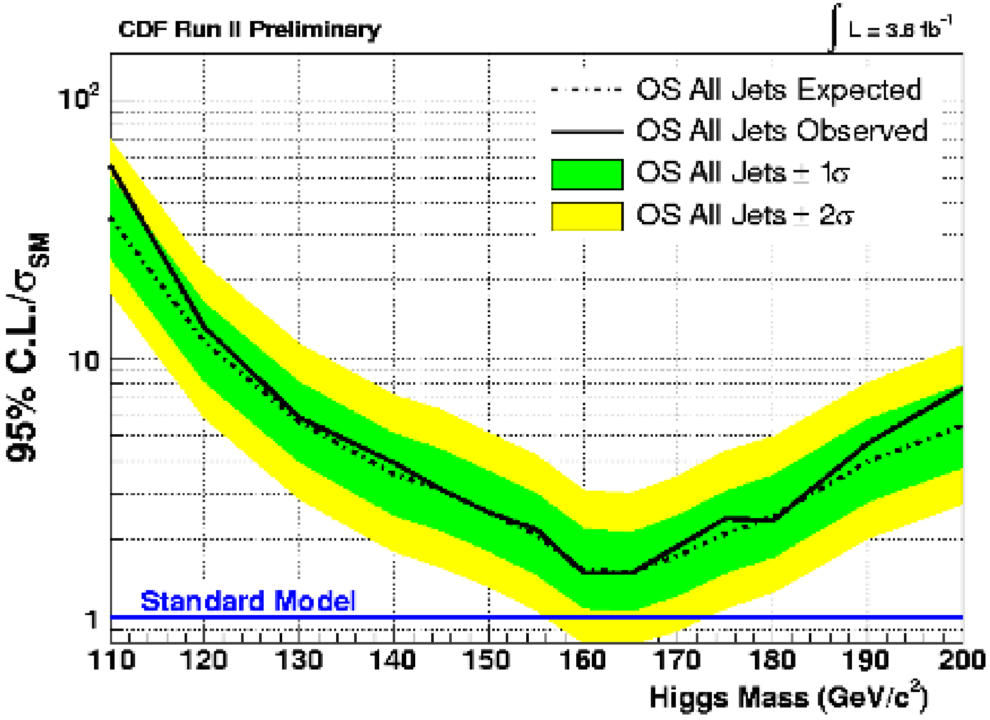


CDF Run II Preliminary	$\int \mathcal{L} = 3.6\ \text{fb}^{-1}$		
$M_H = 160\ \text{GeV}/c^2$			
$t\bar{t}$	100	±	17
DY	33	±	11
WW	17.6	±	4.0
WZ	3.76	±	0.52
ZZ	1.62	±	0.22
W+jets	14.7	±	4.0
$W\gamma$	2.12	±	0.70
Total Background	173	±	23
$gg \to H$	1.75	±	0.30
WH	1.39	±	0.18
ZH	0.693	±	0.090
VBF	0.70	±	0.11
Total Signal	4.53	±	0.52
Data	169		

OS 2+ Jets

$H \rightarrow WW$ Result

- Upper limit on σ×BR obtained likelihood fit of all five NN output distributions.



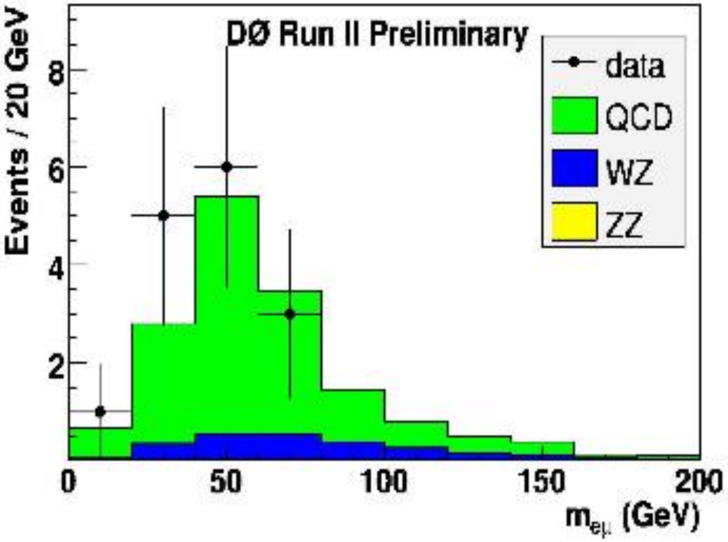
Expected limit is 1.48 times SM at M_H=160 GeV

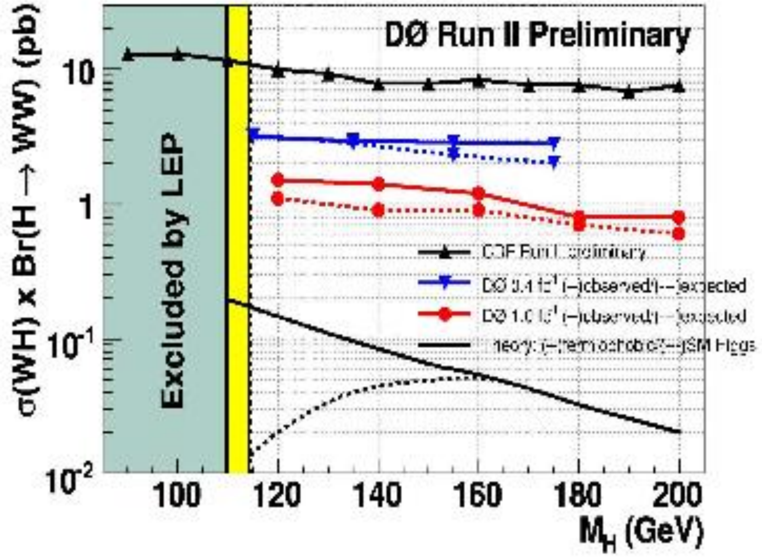
$WH \to WWW \to \ell^+ \ell^+$

- Signature two like-sign high p_T leptons ($\ell = e$ or μ).
- Smaller σ×BR than $H \to WW$ but very low SM background.
- Backgrounds: WZ, ZZ, W+γ/jets, QCD, charge flips.
  - Instrumental backgrounds (fakes and charge flips) are dominant.

$WH \rightarrow WWW \rightarrow \ell^+ \ell^+$

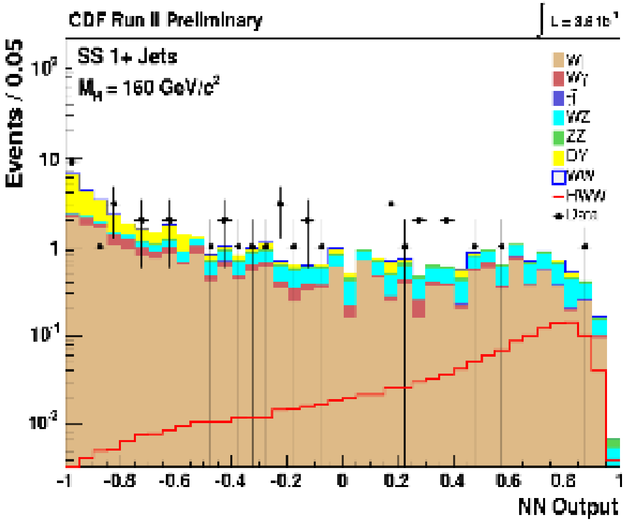
- Event selection: $p_T(e) > 15$ GeV, $p_T(\mu) > 15$ GeV.
- Upper limit on $\sigma \times BR$ from 2D multivariate likelihood fit.
  - Expected limit is 17 times SM at M_H=160 GeV.

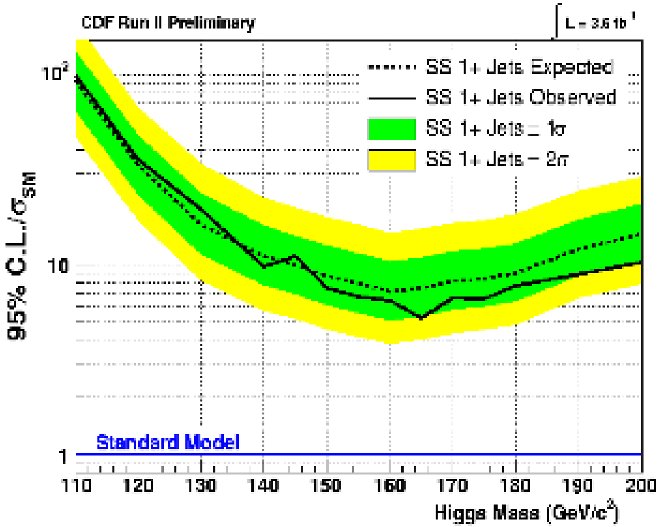




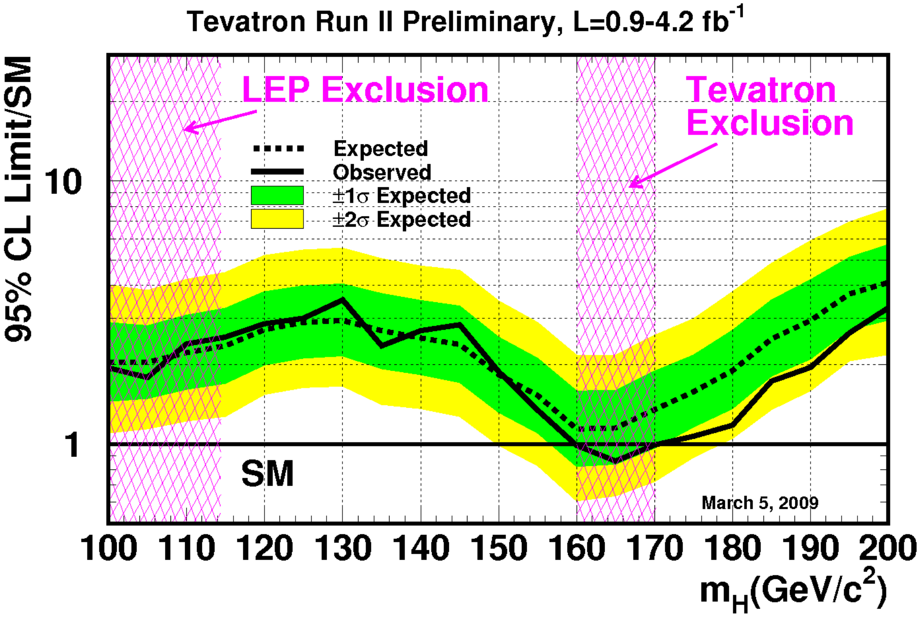
$WH \rightarrow WWW \rightarrow \ell^+\ell^+$

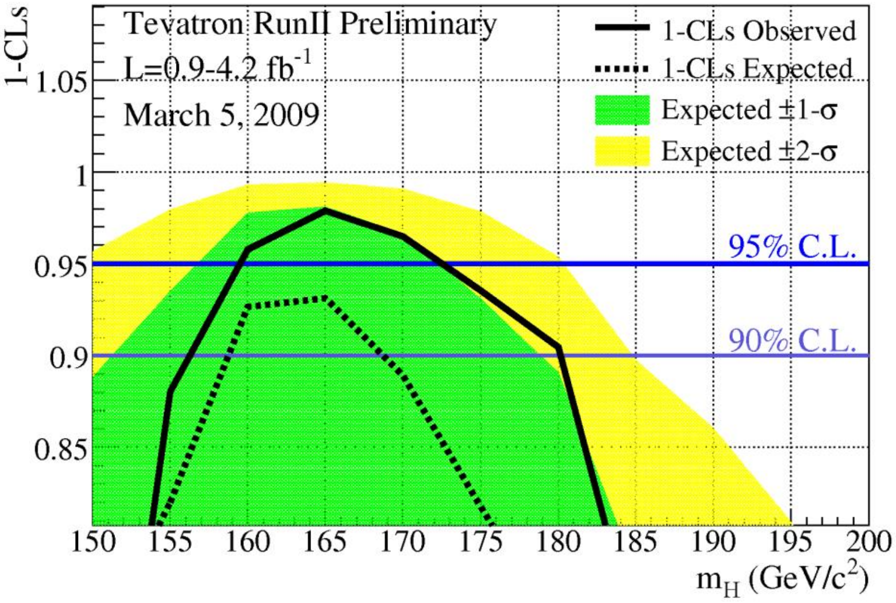
- Event selection: $p_{T1} > 20$ GeV, $p_{T2} > 20$ GeV.
- Multivariate analysis using 13-variable NN.
  - Expected limit is 7.2 times SM at M_H=160 GeV.



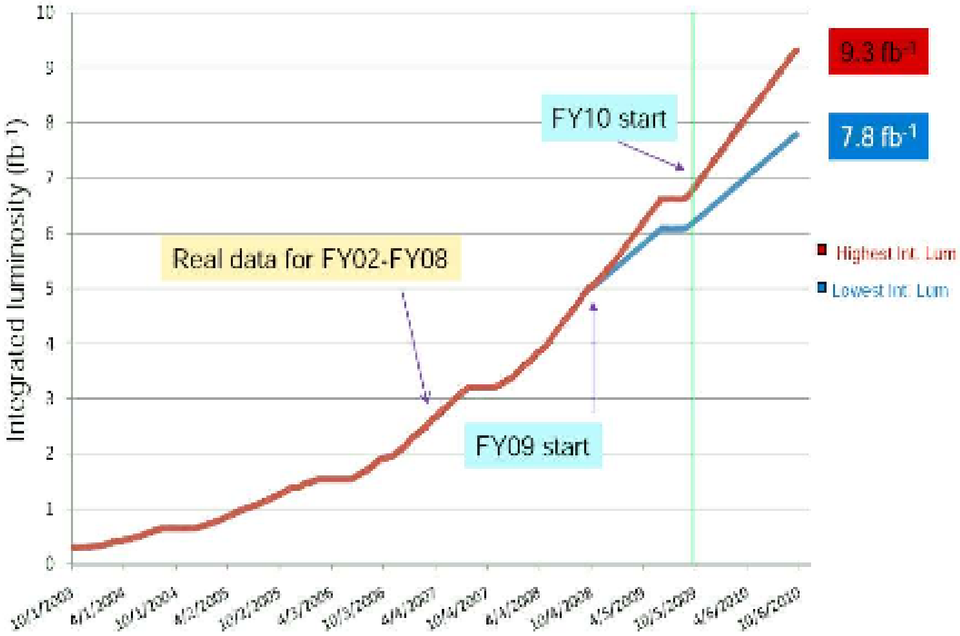


Tevatron CDF & D0 combined March 2009





Prospects



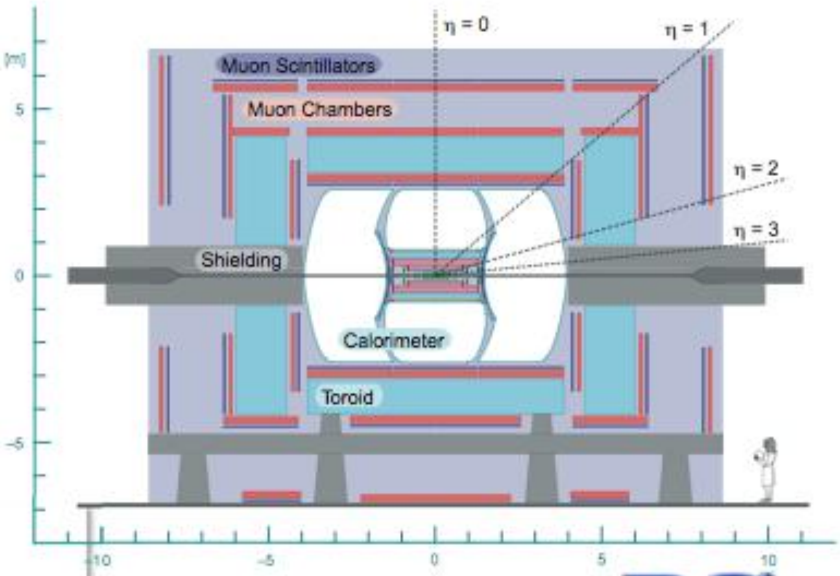
- Tevatron and experiments are running well.
- Experiments have ~6 fb^{-1} delivered today (~5.3 fb^{-1} recorded).
- Expect 8-9 $\mathrm{fb}^{-1}$of integrated luminosity per experiment delivered (7-8 fb^{-1} recorded) by end of FY10 (more if Tevatron runs in 2011).
- Analysis improvements will likely improve Higgs sensitivity faster than luminosity scaling.

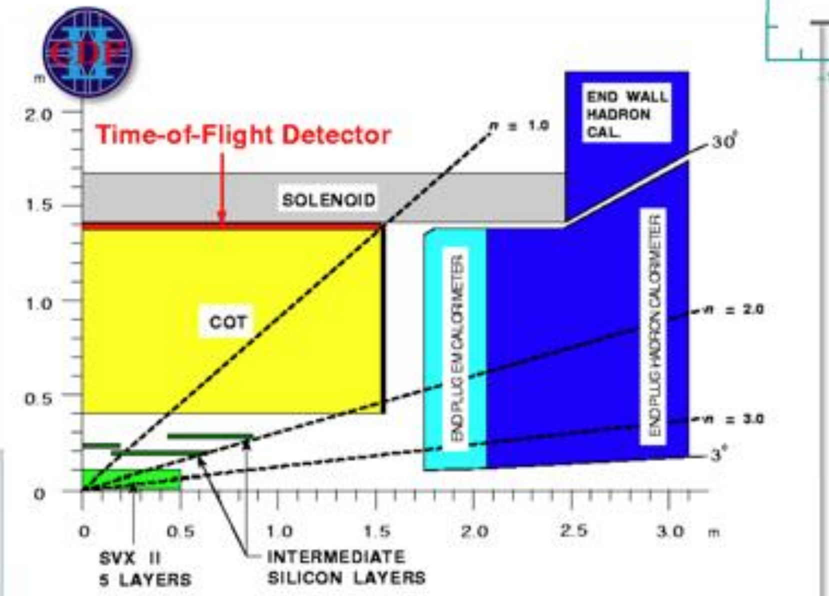
Higgs searches at TEVATRON

Summary

- **SM Higgs excluded at 95% C.L. in the range 160 < M_H < 170 GeV**
- **Tevatron and experiments are continuing to run well**
  - CDF and D0 currently have recorded about 5 fb^{-1} of data
  - Expect 7-8 fb^{-1} or more of analized data by the end of 2010

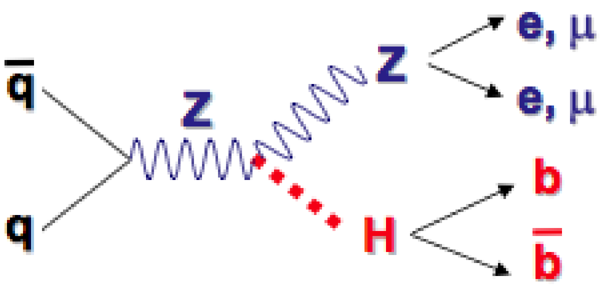
- ✓ Tracking: silicon tracker + drift chamber
  - ✓CDF |η|<2 scint
  - ✓D0 |η|<3
- ✓ Calorimeters: central, wall, plug coverage:
  - ✓ CDF |η|<3.6
  - ✓ DO|η|<4.2
- ✓ Muon coverage |η|<2

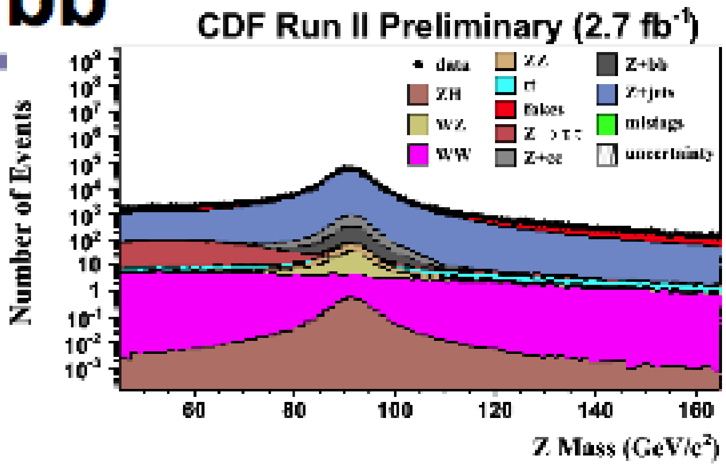




2 lepton: **ZH → ll bb**

Lumi:
CDF: 2.7 fb^{-1}
DØ : 2.3 fb^{-1}





Signature: 2 leptons + 2 b-jets

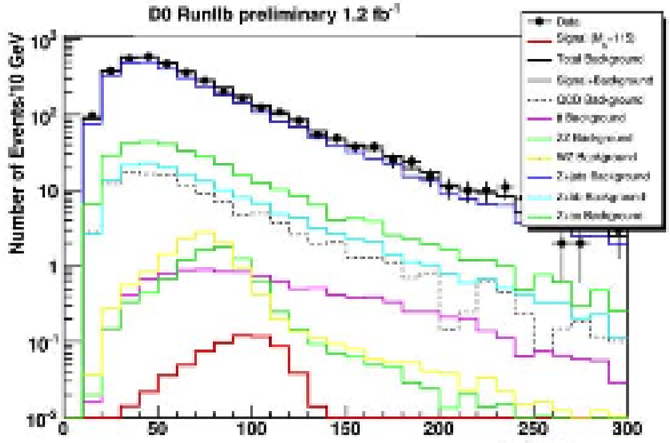
- Lepton requirement

  CDF: 1st (2nd) p_T > 18(10) GeV

  → Define Loose, Tight category

  DØ : p_T > 10 GeV

  Z mass window cut is applied.



- Jets requirement

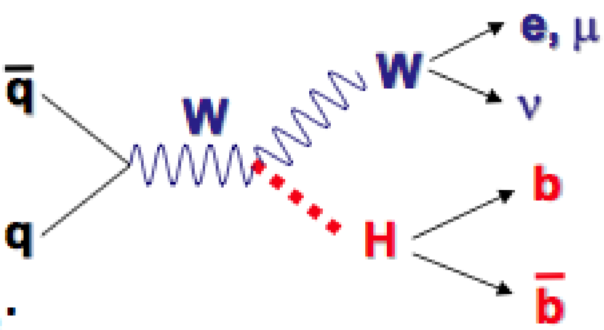
  Pt > 15 GeV, |η| < 2.5

CDF:
improve dijet mass res. from MET.

S/N w/ b-ID	CDF (tight, loose)	DØ
b-ID	Signal / BG	Signal / BG
Ti-Ti (Lo-Lo)	1 / 51	1 / 237
Lo-Ti	1 / 89	------
Ti	1 / 293	1 / 508

1 lepton: WH → lν bb

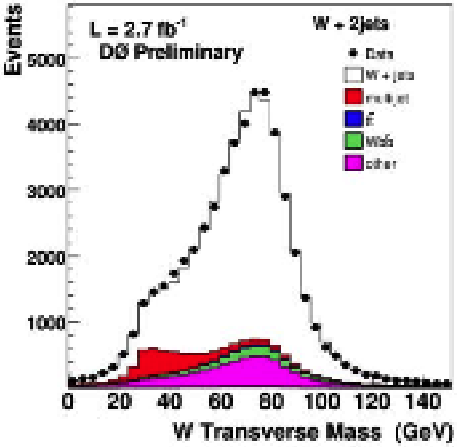
Lumi:
2.7 fb^{-1}

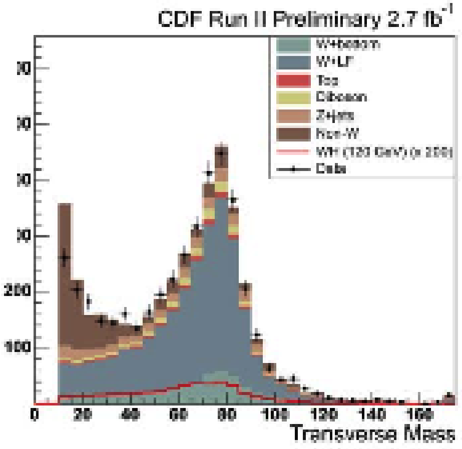


Signature:
1 e/μ + MET + 2 b-jets

- Lepton and MET
  - DØ : p_T > 15 GeV, MET > 20 GeV
  - CDF: p_T > 20 GeV MET > 20 GeV

iso track event is included.





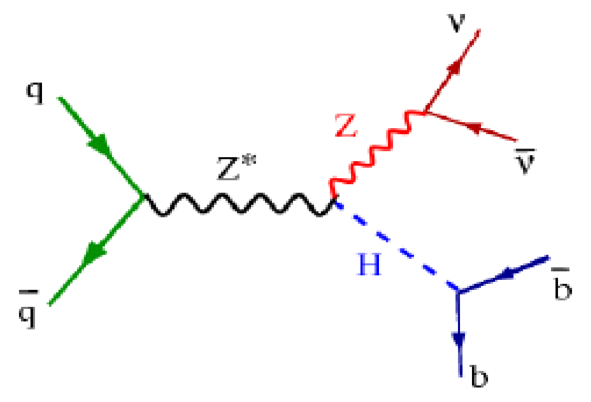
Gain ~ 20% in signal eff. by iso track

- Jets requirement
  - Pt > 20 GeV, |η| < 2.0
    - DØ: 1st jet pt > 25 GeV
    - HT > 60 GeV
  - Cut for reject QCD
  - 2nd lepton veto

Yield with b-ID

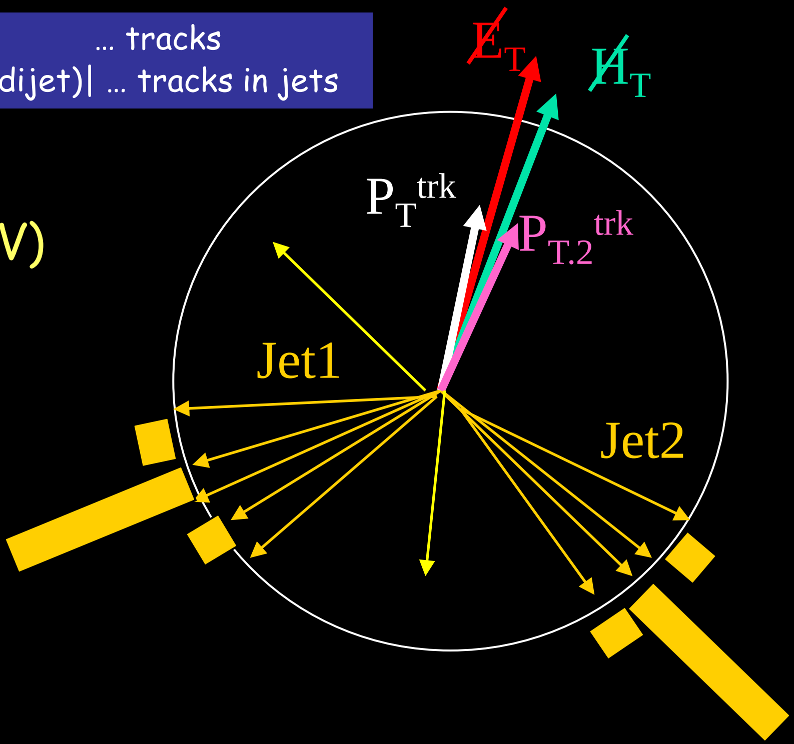
	CDF		DØ (2jet, 3jet)	
b-ID	Signal	BG	Signal	BG
Ti-Ti (Lo-Lo)	1.4	156.5	3.9, 1.0	345,322
Lo-Ti	2.0	146.2	----	----
Ti	4.6	1760	6.8, 1.6	2182,963

$Z(\rightarrow\nu\bar{\nu})H(\rightarrow b\bar{b})$ Search (1)



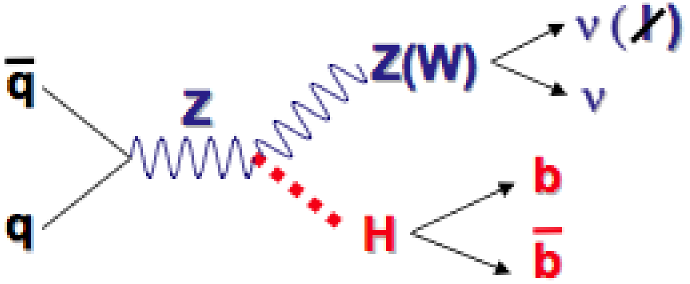
- An important channel for low-mass Higgs search
  - Large $B(Z\rightarrow\nu\nu) \sim 20\%$
- Trigger on events with large missing H_T
  - H_T is defined as the magnitude of the vector sum of jets' E_T
- Analysis was based on 261 pb^{-1}
- Selection:
  - 2 Jets:
    - $E_T > 20$ GeV, $|\eta|<2.5$
  - Missing $E_T > 25$ GeV
  - Veto events with isolated tracks (p_T>8 GeV)
    - To reject leptons from W/Z
  - $H_T = \Sigma|p_T(\text{jets})| < 200$ GeV
    - To reject tt events
  - Reduce "instrumental" backgrounds
    - Jet acoplanarity $\Delta\phi(\text{dijet}) < 165°$
    - Use various missing energy/momentum variables
    - Form asymmetry variables

$P_T^{trk} = -|\Sigma p_T(trk)|$ … tracks
$P_{T,2}^{trk} = -|\Sigma p_T(\text{trk in dijet})|$ … tracks in jets

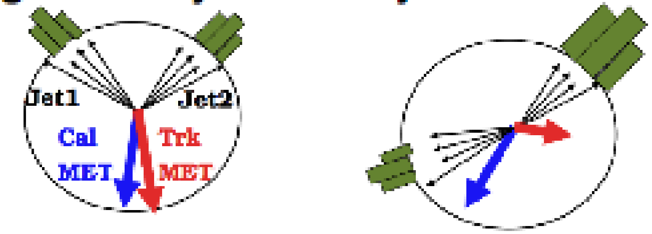


0-lepton: **VH** → νν **bb**

Lumi:
2.1 fb^{-1}



Signal: νν+jet   MJ: jet + mis-meas.

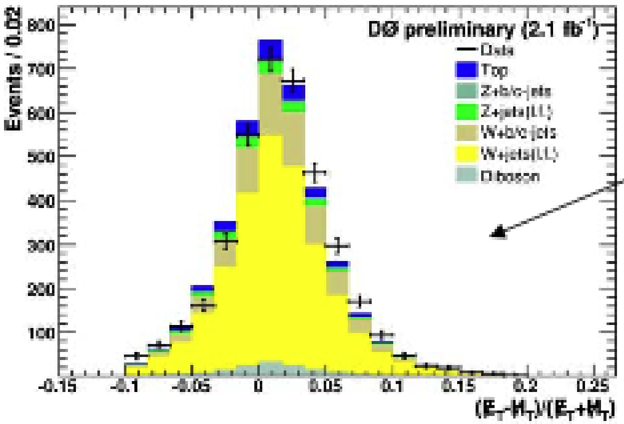


Cal MET ≠ Trk MET

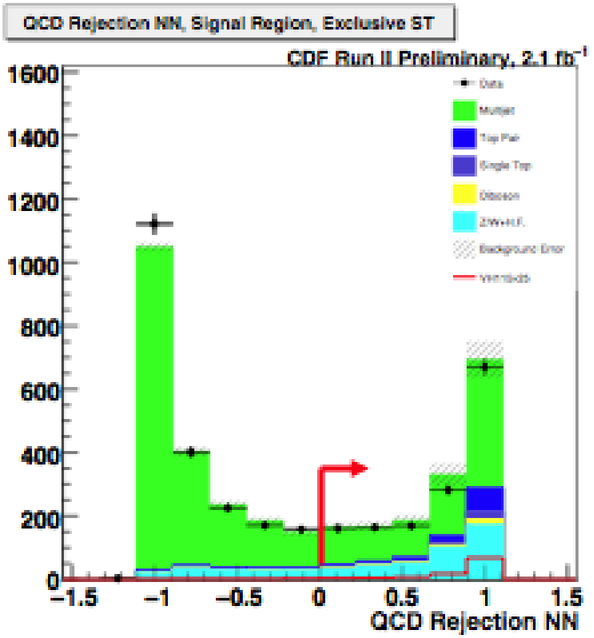
- Signature : MET + 2 jets.
  CDF: MET>50 GeV, Jet1(2) p_T >35 (25) GeV
  DØ : MET>50 GeV, p_T >20 (20) GeV

- To handle Multi-jet BG
  - Signal sample
  - Control region
    - QCD control sample
    - EW control sample

QCD rejection
D0 : Δϕ (CalMET, TrkMET)
CDF: Train NN to reject QCD.



EW cont. sample



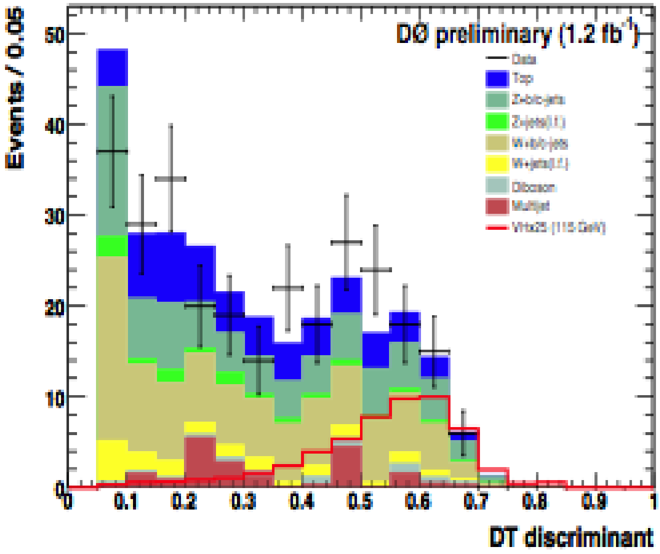
0-lepton: ZH → νν bb result

- Yield after b-ID

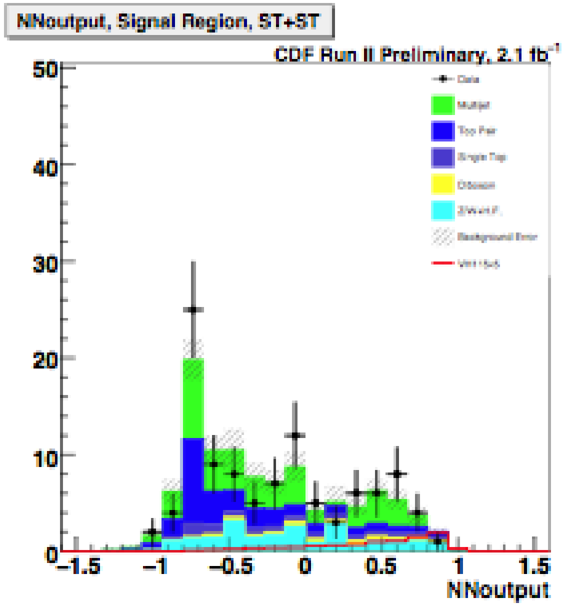
	CDF		DØ (2jet or 3jet)	
b-ID	Signal	BG	Signal	BG
Ti-Ti	1.9	105	----	----
Lo-Ti	1.5	149	3.7	442.8
Ti	4.0	1443	----	----

- MVA

DØ : BDT



CDF : BDT



Result:

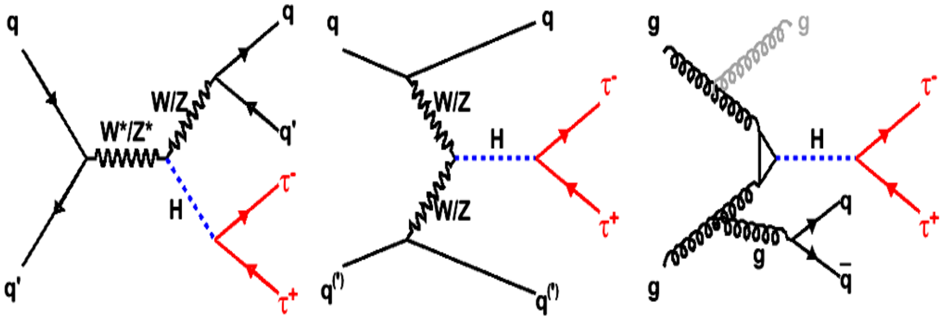
No significant excess.

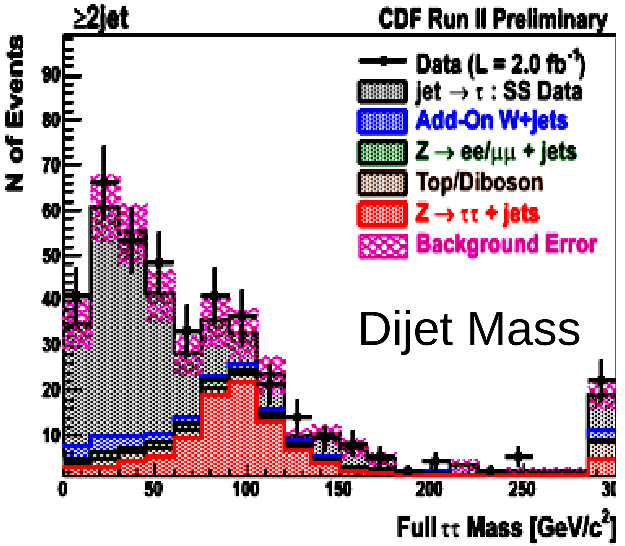
Limit / SM
@ m_H=115GeV

DØ 2.1 fb^{-1}:
exp : 8.4
obs : 7.5

CDF 2.1 fb^{-1} :
exp : 5.6
obs : 6.9

Other channels sensitive at low mass

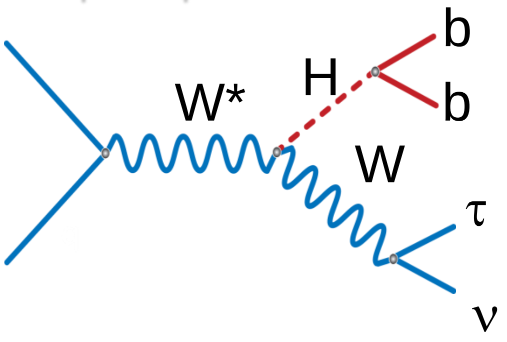




Dijet Mass

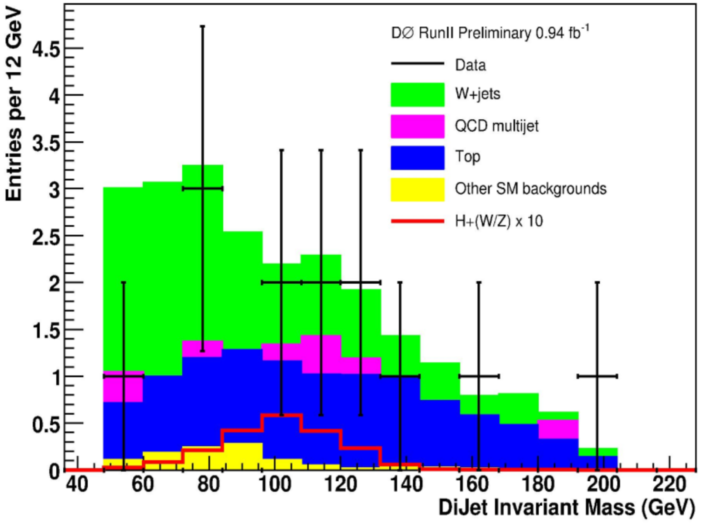
Analysis Technique

- Signature τ had+ τ lep+2 jets
- Simultaneous search in WH+ZH+VBF+ggH
- Use NN to extract signal
- Good proof of principle for LHC



Analysis Technique

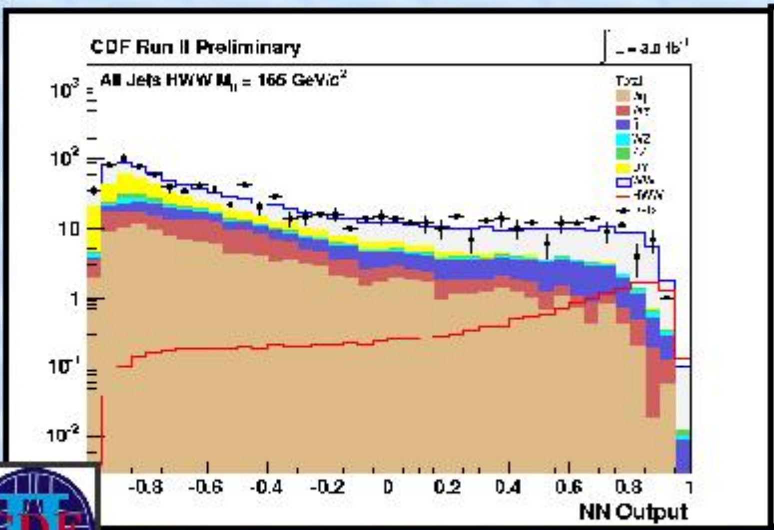
- Hadronic τ + MET + 2 b jets
- Use Dijet mass to extract signal



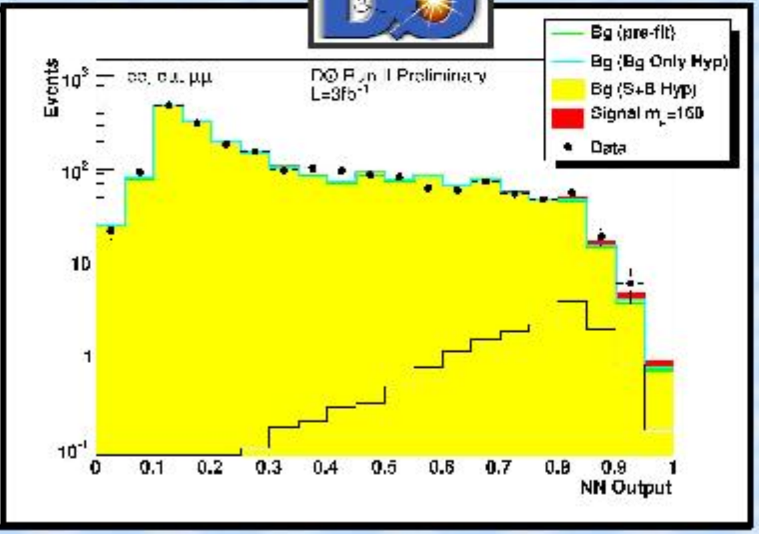
High Mass

H → WW$^{(*)}$ → ll'νν, $\int L = 3.0\ \mathrm{fb}^{-1}$

CDF Search for Higgs to WW* Production using a Combined Matrix Element and NN Technique



NN is used in each of the three di-lepton channels



EXPERIMENT	EXP. Limit/SM m_H=165 GeV/c²	OBS. Limit/SM m_H=165 GeV/c²
DØ	1.9	2.0
CDF	1.6	1.7