Standard Model Higgs searches at Tevatron

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For the CDF and DØ collaborations

Aspen Winter Conference 2007

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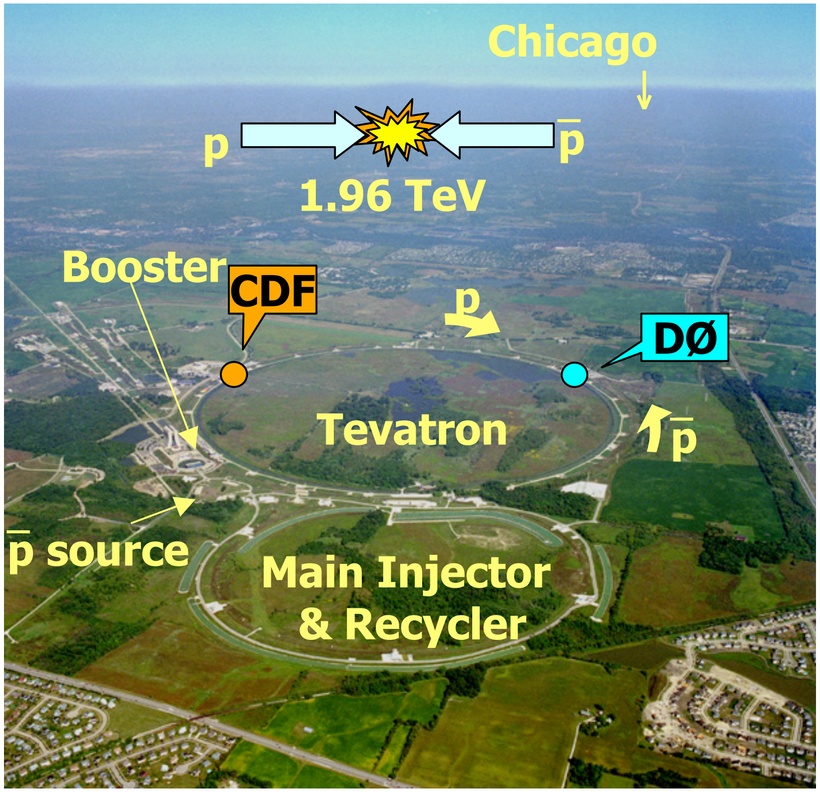
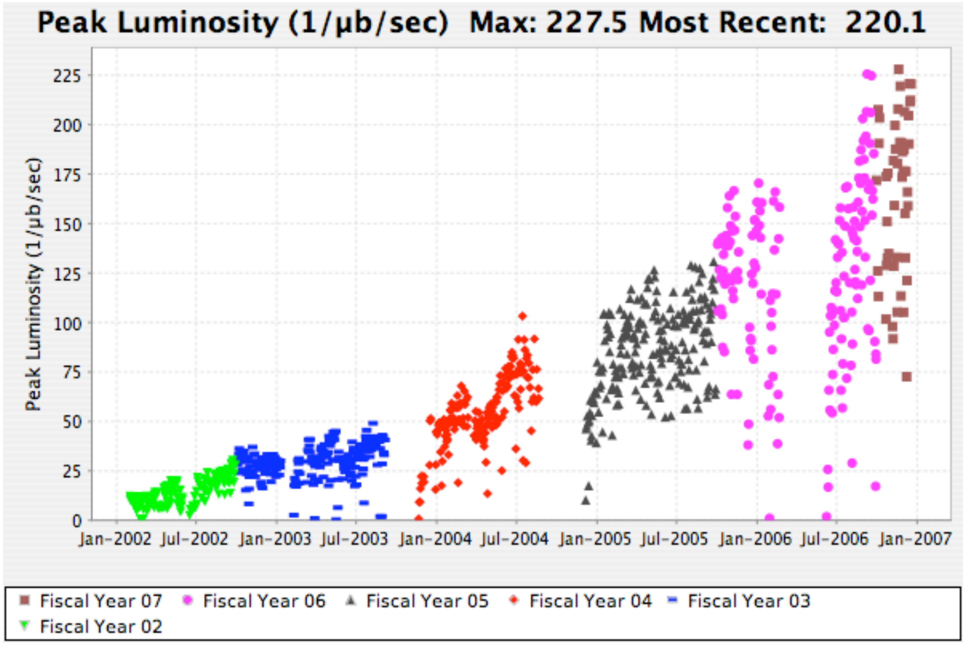
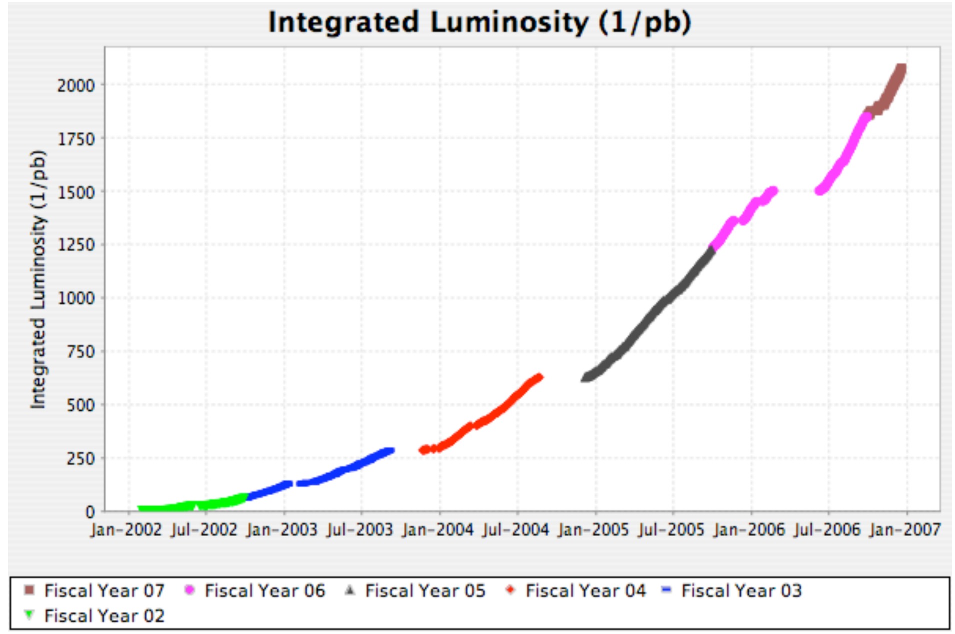


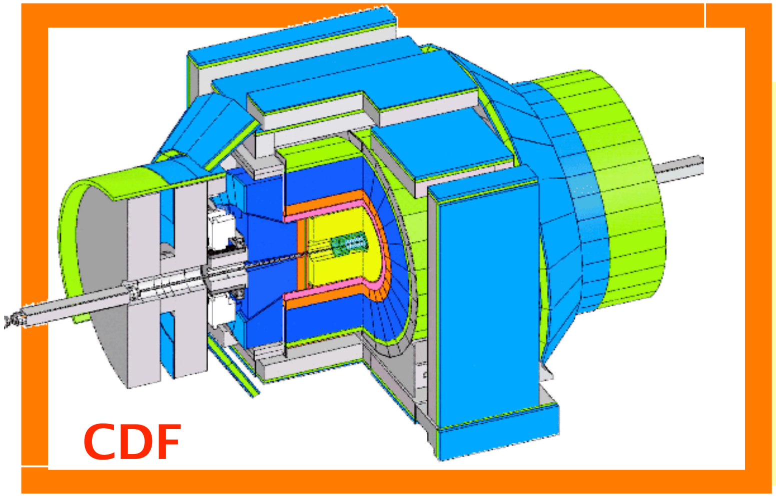
Tevatron Performance



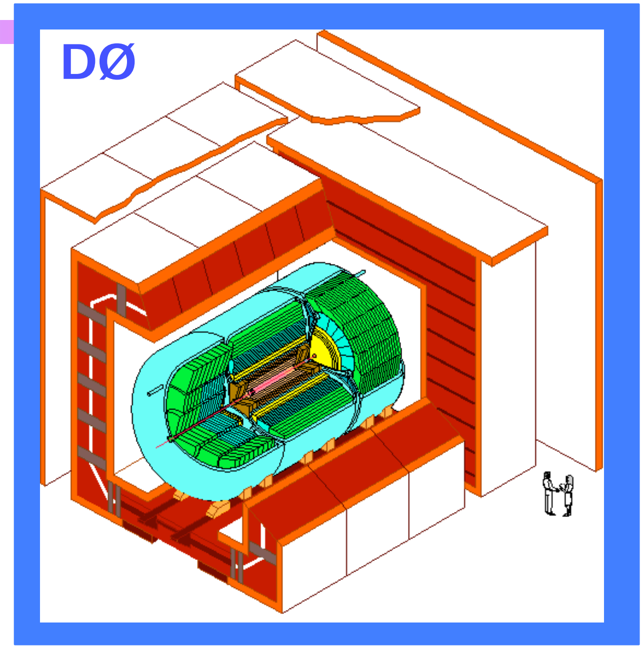


- Record High:
  - Peak luminosity: 227.5×10^{30} cm^{-2}s^{-1}
  - Weekly integrated luminosity: 42.3 pb^{-1}/week
- Total delivered integrated luminosity: 2.2 fb^{-1}

CDF & DØ Detector Upgrades



Upgrades enhance the ability to make sensitive searches

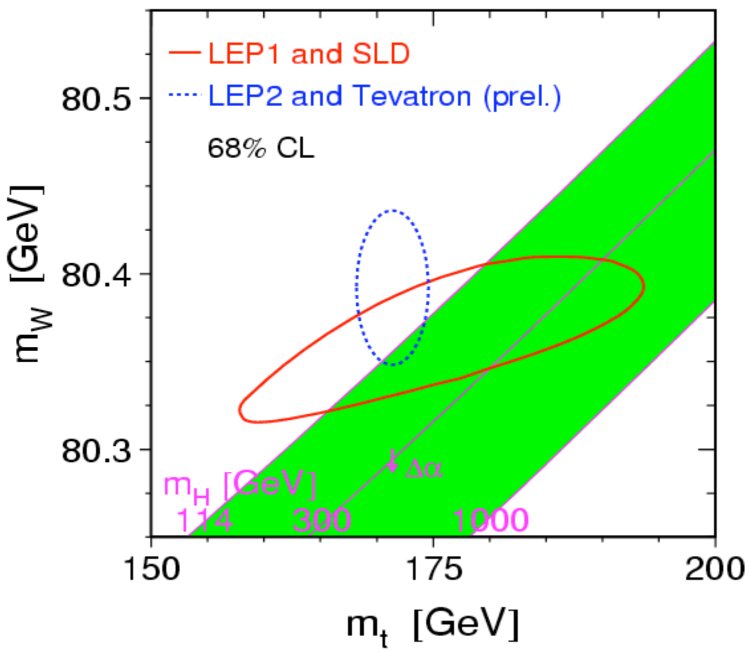


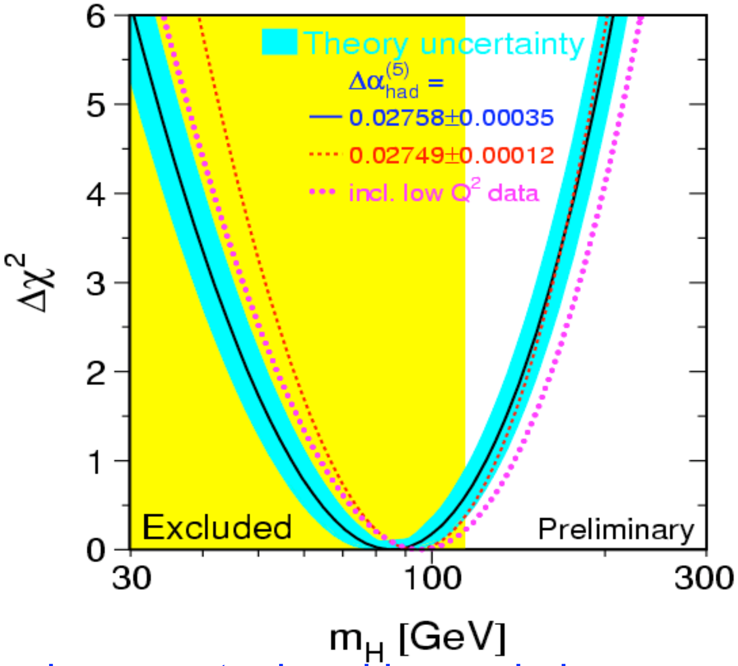
- New central drift chamber and silicon tracker
- New forward calorimeters ("plug") $(1<|\eta|<3)$
- New TOF, extended muon coverage
- improved tracking & secondnary vertex trigger

- New Silicon and Fiber tracker in 2T magnetic field
- Added preshower detector in front of calorimeter
- Improved muon system
- New DAQ and trigger system
- Layer 0 detector is added
- New calorimeter track trigger system

RunIIb upgrade

Experimental Constraints

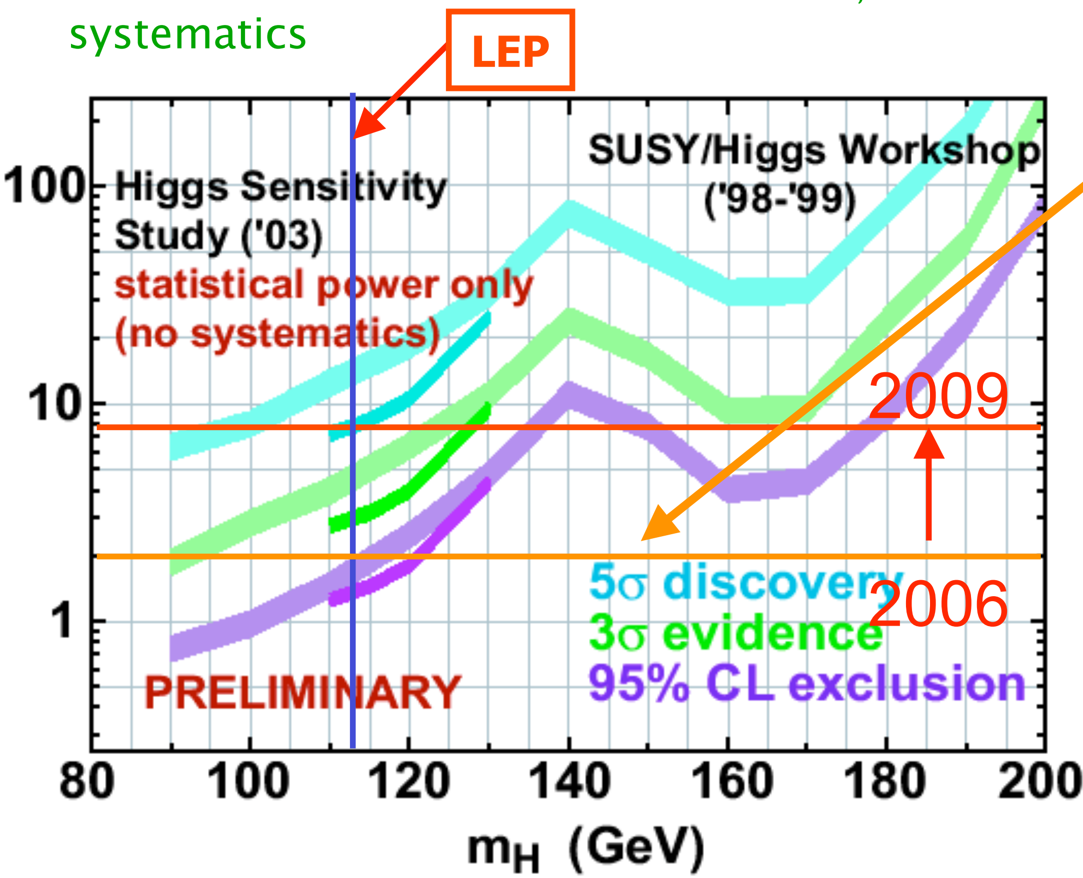




- The Higgs mechanism is the key of Electro-Weak symmetry breaking and gives masses to elementary particles, with its own mass unpredicted
- Direct searches at LEP2: m_H > 114.4 GeV at 95% C.L.
- Indirect limit from fits to precision EW measurements from LEP, SLC, and Tevatron: mH < 166 GeV at 95% C.L. (< 199 GeV if LEP2 limit included)
- Indirect best fit value: 85^{+39}_{-28} GeV at 68% C.L.
- A light Higgs is favored

Higgs sensitivity

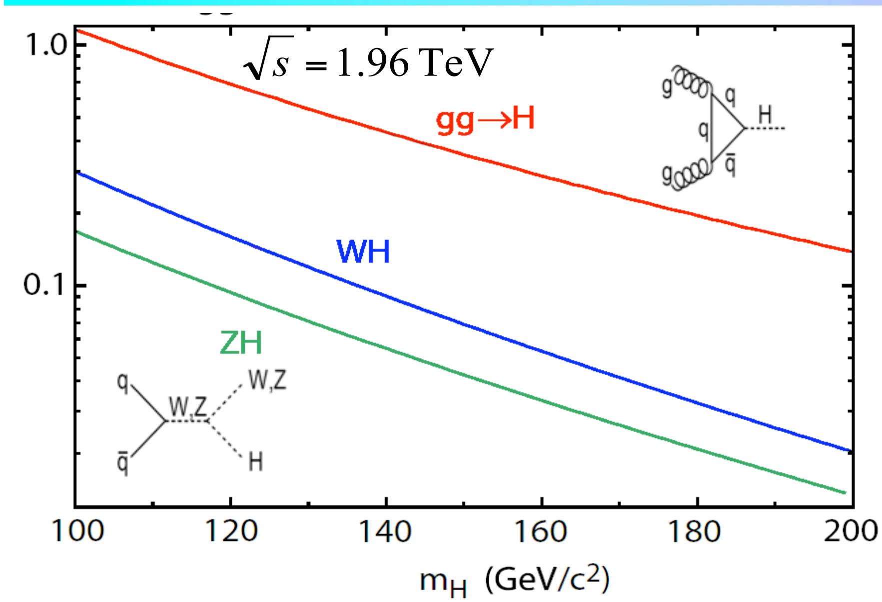
The integrated luminosity (fb) required per experiment, to either exclude a SM Higgs at 95% C.L. or discover it at the 3s or 5s level; no systematics

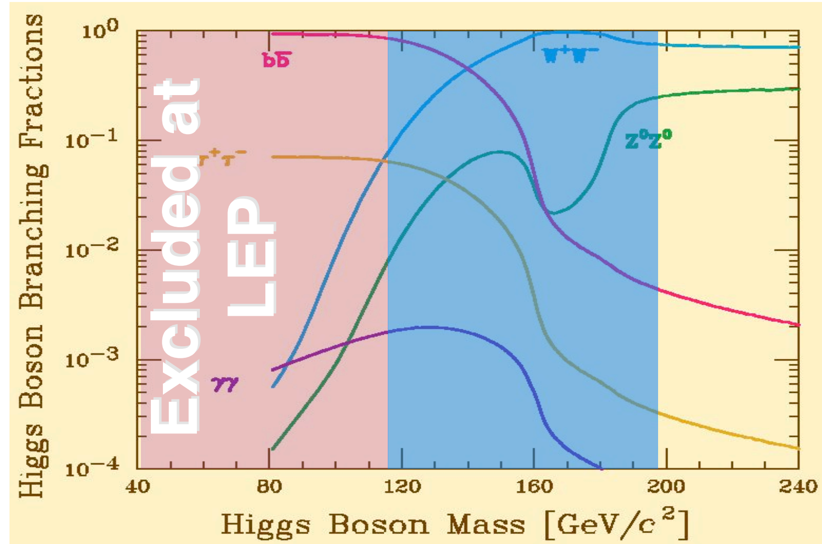


Tevatron entered sensitive region with 2 fb^{-1} already by the end of 2006

- No single channel guarantees success
- Combine two experiment's results
- Improved understanding of detectors is necessary
- Need advanced analysis techniques to maximize sensitivity

SM Higgs Production and Decay





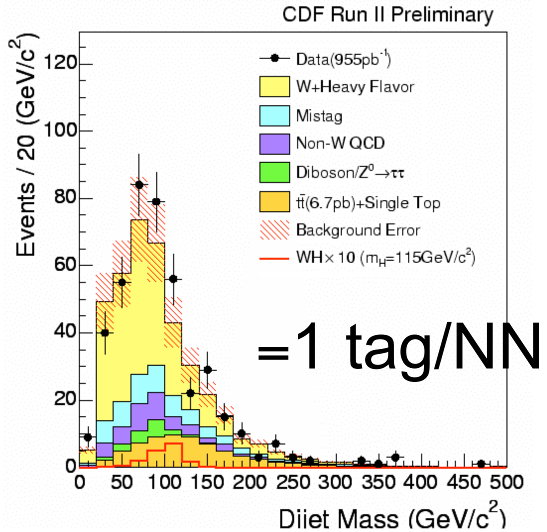
Production cross section (m_H 115-180)
→ in the 0.8-0.2 pb range for gg → H
→ in the 0.2-0.03 pb range for WH
associated vector boson production

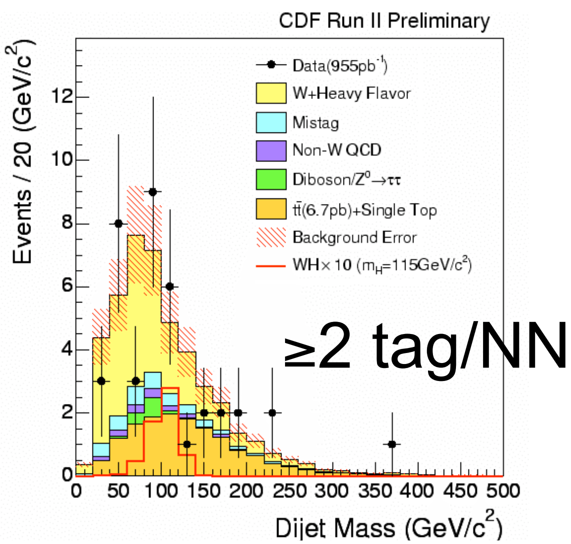
Dominant Decays
→ bb for M_H < 135 GeV
→ WW* for M_H > 135 GeV

Search strategy:

M_H <135 GeV: associated production WH and ZH with H→bb decay
Backgrounds: Wbb, Zbb, top, WZ,QCD **complement with WWW* & WW***
M_H >135 GeV: gg →H production with decay to WW*
Backgrounds: WW, DY, W/ZZ, tt, tW, ττ **complement with WWW***

WH → lνbb

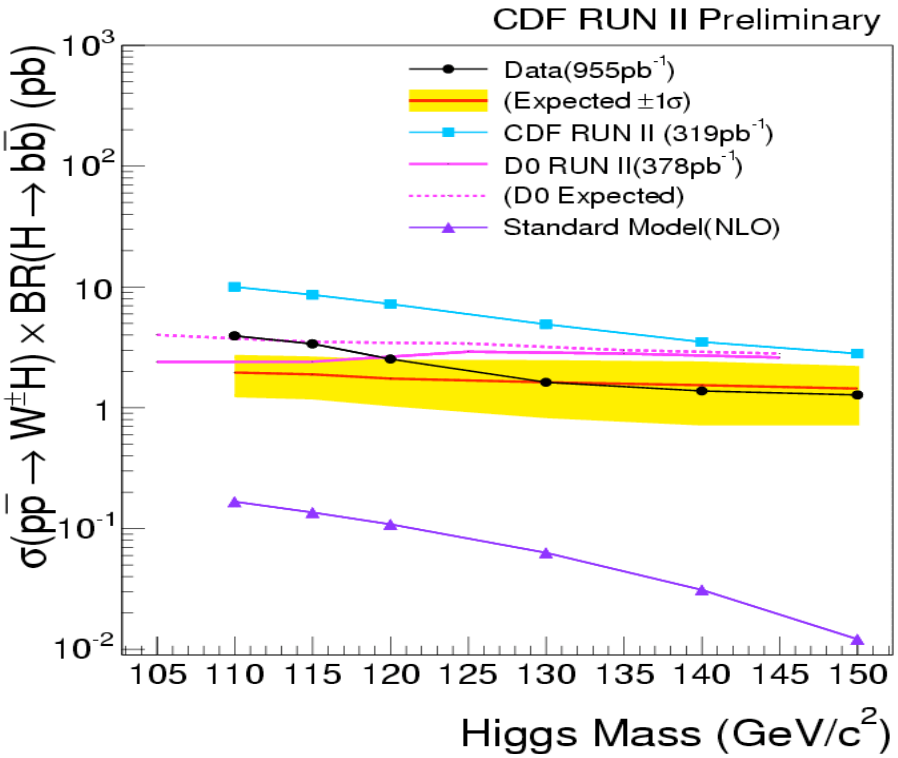




- Best Channel for low mass higgs
- Event signature:
  - A high p_T lepton (e,μ)
  - Large missing E_T
  - Two *b*-jets (≥1 *b*-tag)
- Backgrounds: Wbb,Wcc,W+jets (mistags),Diboson,Top,Multijet

Jet Multiplicity	2jet	3jet	$\geq$ 4jet
Observed Events(Before b-tagging)	14604	2362	646
Mistag	3.5 ± 0.5	2.0 ± 0.3	1.2 ± 0.2
$Wb\bar{b}$	20.3 ± 7.0	5.7 ± 1.8	1.0 ± 0.4
$Wc\bar{c}$	3.3 ± 1.1	0.4 ± 0.1	0.1 ± 0.04
Wc	-	-	-
$t\bar{t}$(6.7pb)	10.4 ± 2.3	29.5 ± 6.4	45.5 ± 9.9
Single Top	4.2 ± 0.7	1.4 ± 0.2	0.3 ± 0.1
Diboson/$Z^0 \to \tau\tau$	1.2 ± 0.3	0.3 ± 0.1	0.1 ± 0.1
non-W QCD	1.4 ± 0.3	0.9 ± 0.2	0.3 ± 0.1
Total Background	44.2 ± 8.5	40.1 ± 6.8	48.6 ± 10.0
Observed Events($\geq$2tag)	39	44	65

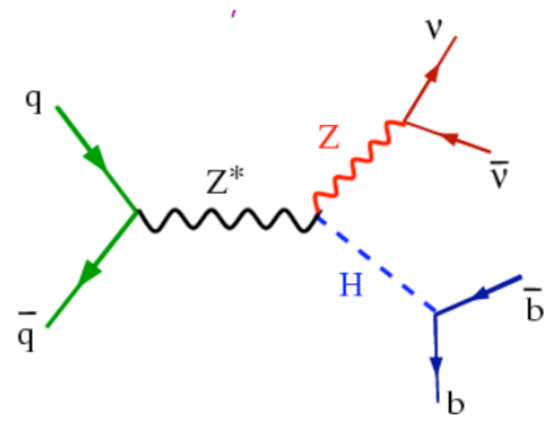
WH → lνbb



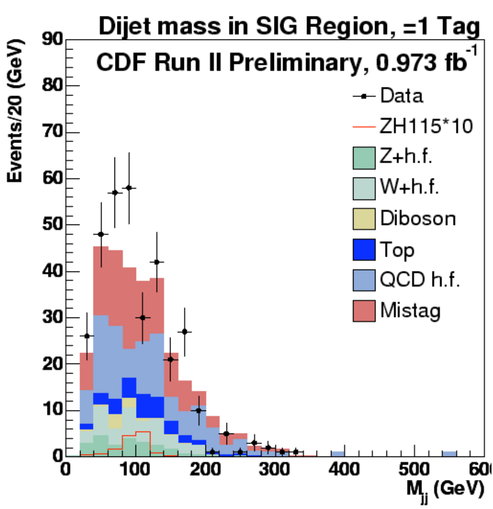
Higgs Mass (GeV/c^2)	Upper Limit (pb) Observed	Expected
110	3.9	2.2
115	3.4	2.2
120	2.5	2.0
130	1.6	1.8
140	1.4	1.7
150	1.3	1.5

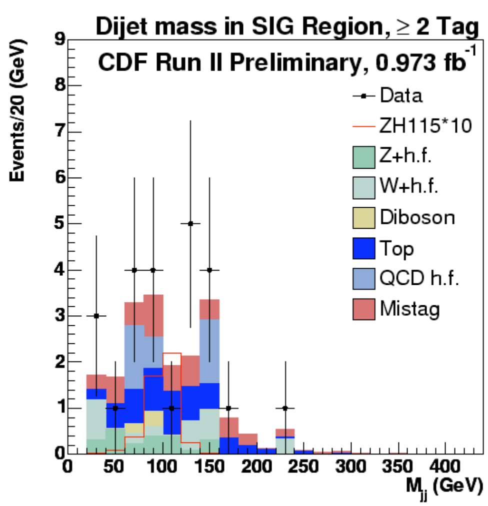
- σ(pp -> WH)×BR(H->bb) < 3.9 - 1.3 (pb)
- Higgs masses from 110GeV/c^2 to 150GeV/c^2 (95% C.L.)

ZH→ννbb(or WH → ~~l~~νbb)



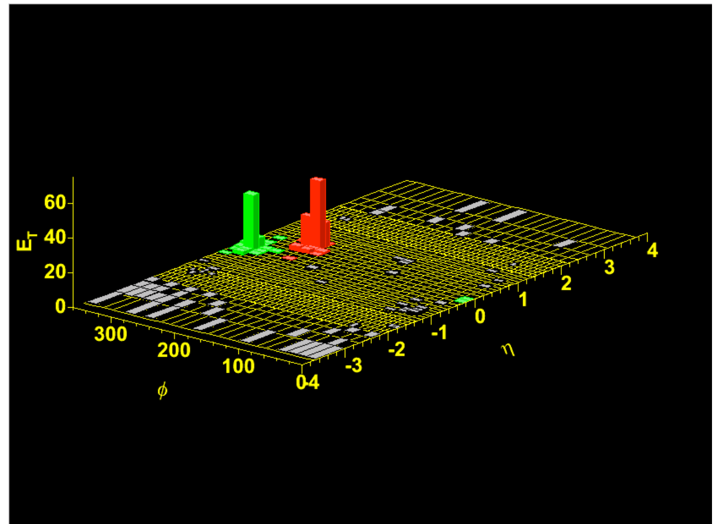
- Low mass higgs channel
- Event signature:
  - **Large missing E_T**
  - **Two *b*-jets (≥1 *b*-tag)**
- Backgrounds: W+h.f,Z+h.f, WZ,ZZ,top production, multijets,W+jets(mistag)
- Optimization: Kinematics
  - **Δφ(Leading Jet,$\not\!E_T$)**
  - **$\not\!H_T/H_T>0.45$**
  - **Leading Jet E_T>60 GeV**
  - **$\not\!E_T$>75 GeV**

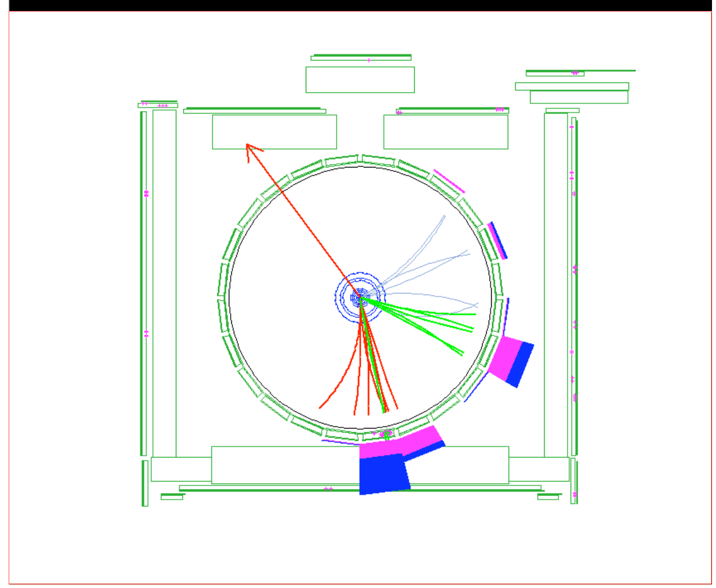




ZH→ννbb(or WH → ~~l~~νbb)

Process	Signal Region(1tag)	Signal Region(2tag)
Multijets	104±25	3.5±1.7
Mistag	110±19	4.8±0.9
Top	28±4	5.5±1.1
W+h.f	36±8	2.9±1.4
Z+h.f	24±5	2.3±0.6
Diboson	7.1±1.1	0.6±0.1
ZH(115 GeV)	0.77±0.09	0.25±0.05
WH(115 GeV)	0.64±0.07	0.22±0.04
Total Expected BG	310±40	19.6±3.1
Observed	333	24

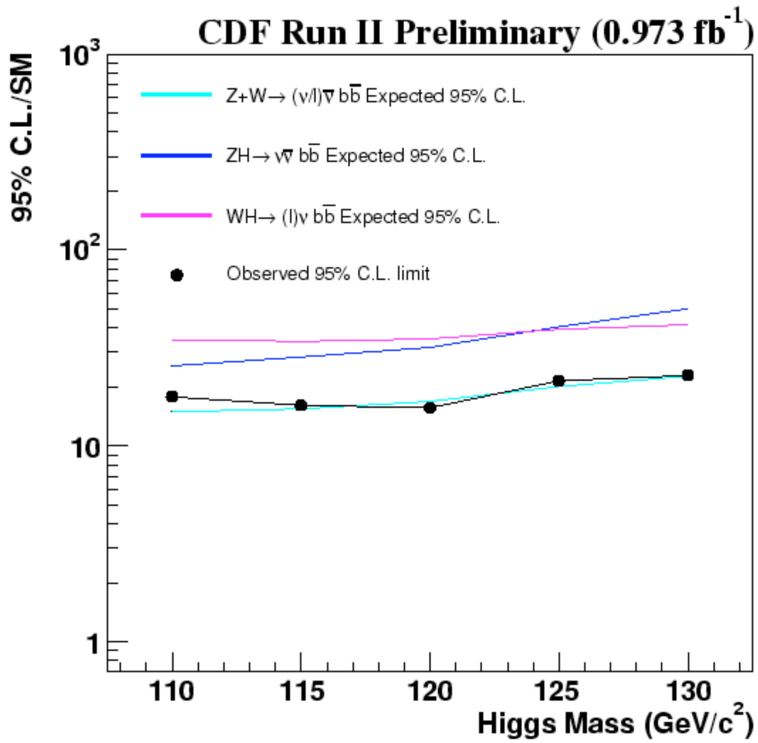




Double Tagged Candidate Event

- Jet Et1 = 100.3 GeV - TAGGED
- Jet Et2 = 54.7 GeV - TAGGED
- Missing Et = 144.8 GeV
- Dijet mass = 82.1 GeV

ZH→ννbb(or WH → lνbb)

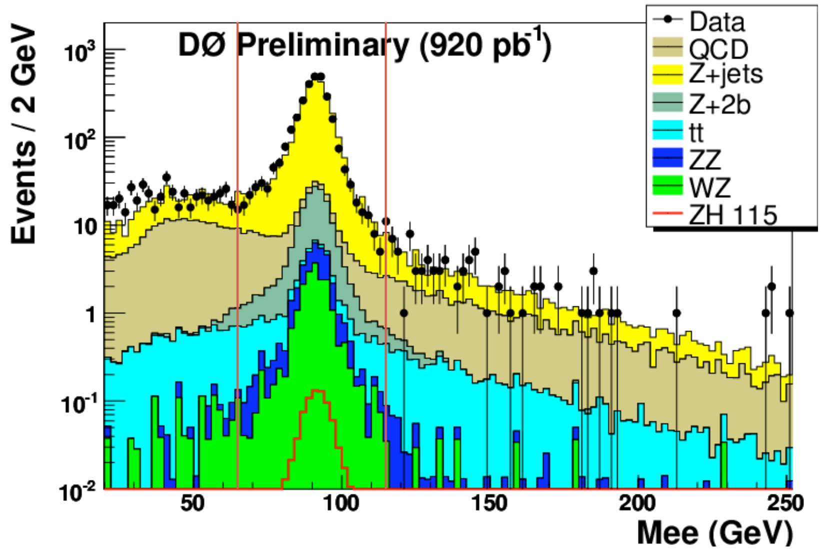


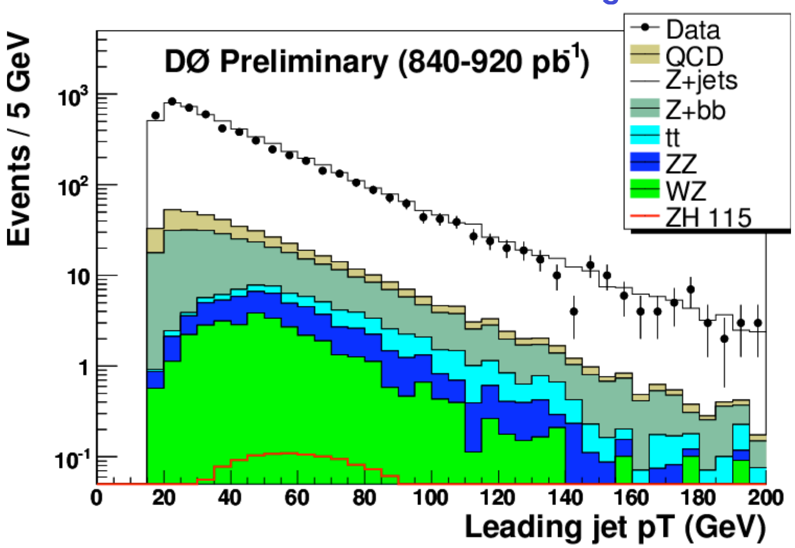
Higgs Mass(GeV)	ZH Exp.	WH Exp.	Combined	Obs.
110	25.5	34.8	14.9	17.8
115	28.4	34.0	15.4	16.0
120	31.7	35.1	16.8	15.6
125	40.5	39.2	20.0	21.4
130	50.0	41.5	22.6	22.8

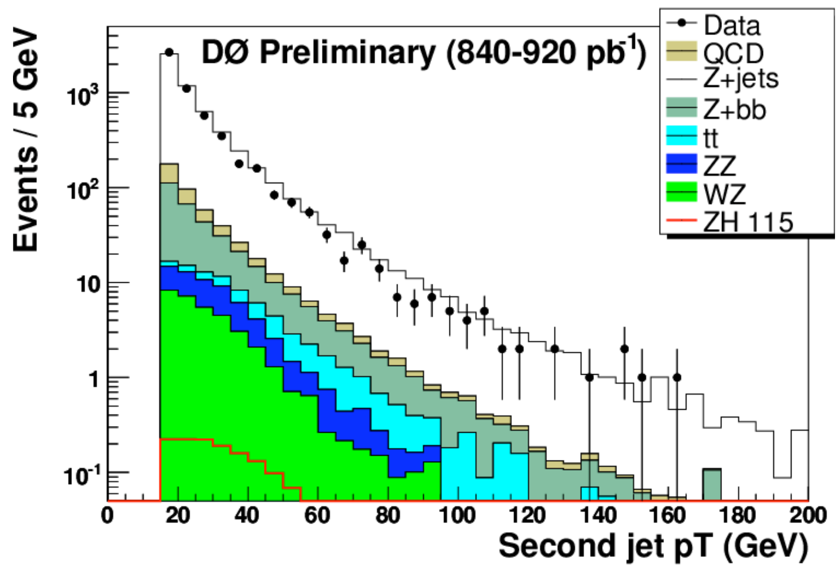
- σ(pp -> ZH) / σ_{SM} < 17.8 - 22.8 (pb)
- Higgs masses from 110GeV/c^2 to 130GeV/c^2 (95% C.L.)

$ZH \rightarrow l^+l^-bb$

- Low mass higgs channel
- Event signature:
  - –A pair of high P_T lepton with an invariant mass constraint
  - –At least two *b*–jets (≥1 *b*–tag)
- Backgrounds: Z+jets, Zbb, top, WZ, ZZ, multijet



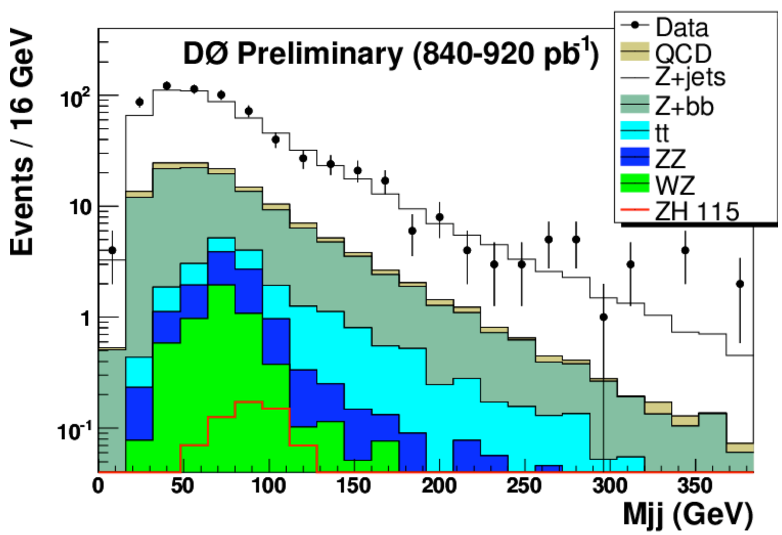


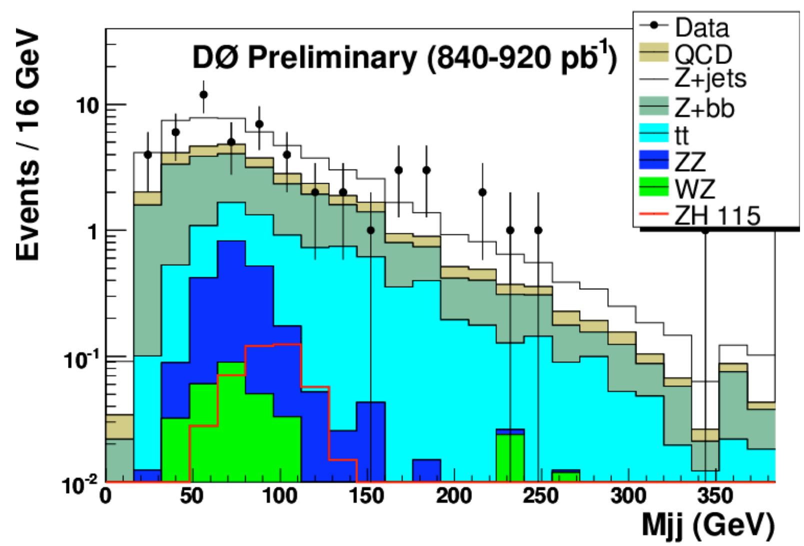


ZH → l^+l^-bb

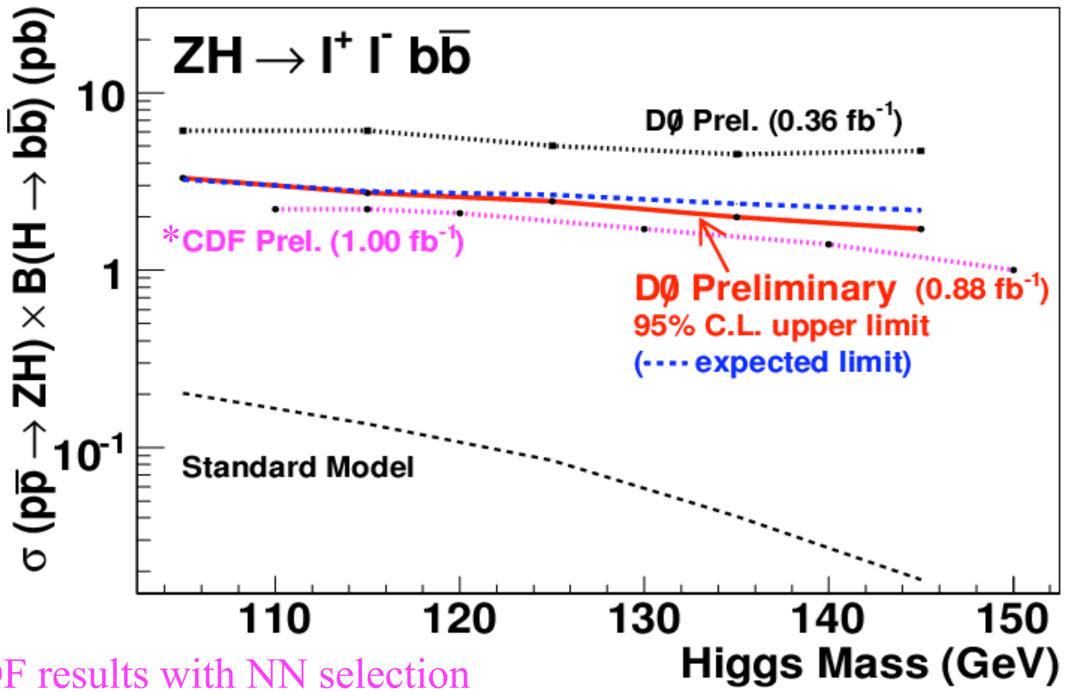
1 *b*-tagged jet (Mjj 60~110 GeV)		
	e^+e^-	$\mu^+\mu^-$
Data	126	99
Bckg.	111 ±22	88 ±18
QCD	4.4	0.4
Z + jets	82.4	75.5
Z + bb	17.8	16.0
tt	2.0	1.8
ZZ	2.2	1.4
WZ	2.3	2.0
ZH 115	0.243 ±0.011	0.21 ±0.009

≥2 *b*-tagged jets (Mjj 60~110 GeV)		
	e^+e^-	$\mu^+\mu^-$
Data	8	10
Bckg.	9.8 ±3.4	8.7 ±3.1
QCD	0.25	1.8
Z + jets	3.7	3.7
Z + bb	3.8	3.4
tt	1.3	1.2
ZZ	0.11	0.07
WZ	0.75	0.65
ZH 115	0.169 ±0.014	0.14 ±0.012





ZH → l+l−bb



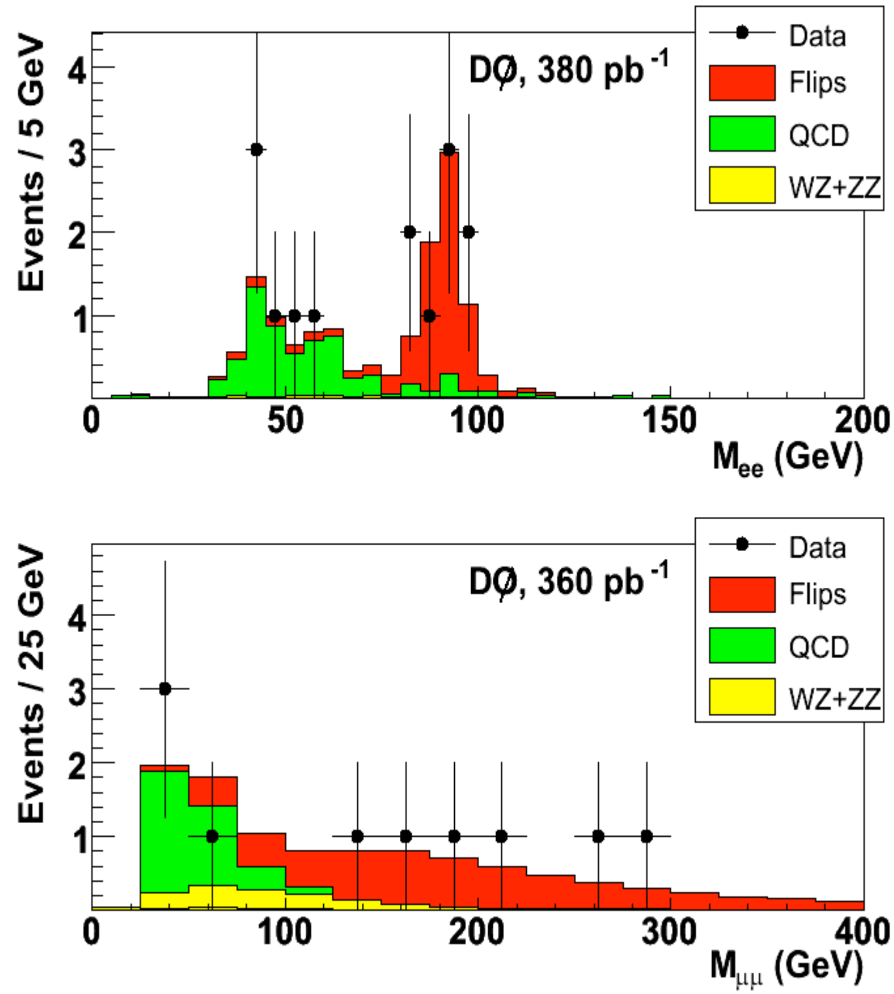
*CDF results with NN selection

- No excess observed, so set cross section limits
- Modified frequentist approach (CL_S), using di-jet mass distribution
- 95% C.L. on *ZH* cross section: 3.3-1.6 pb for m_H=105-155 GeV
- Advanced Analysis (NN) and 12% more data in CDF improved the limits

WH→WWW*→$l^{\pm}\nu l^{\pm}{}'\nu'$+X (2 like-sign leptons)

Low BR, but channel important in the "intermediate region" 125-145 GeV

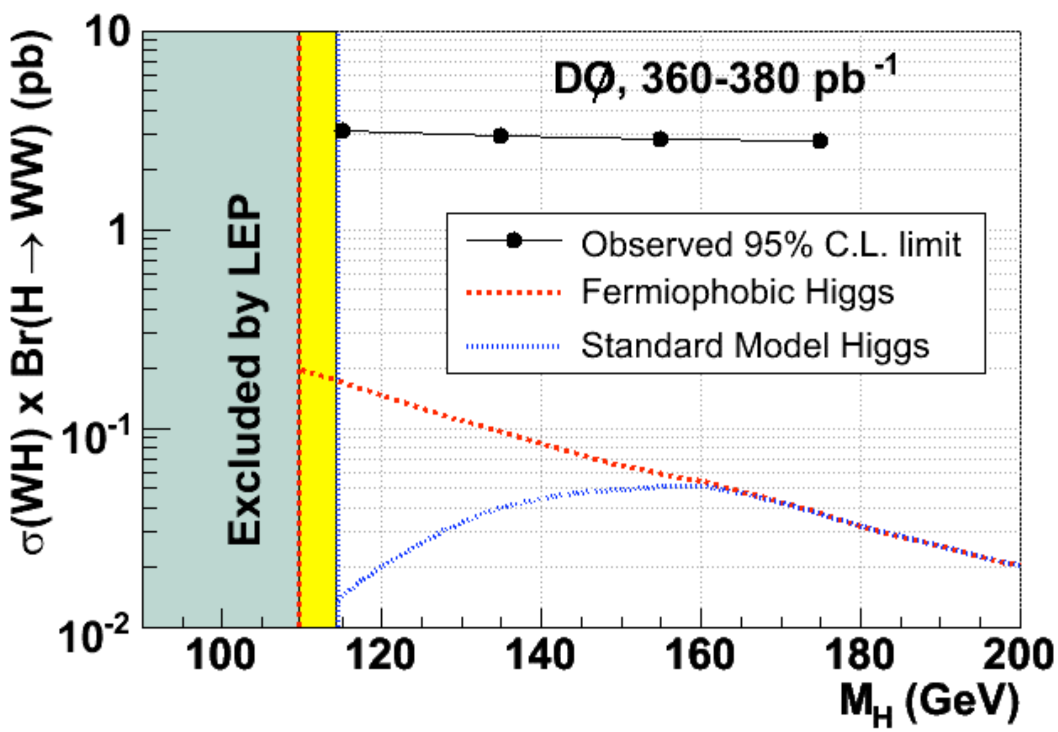
- Event Signature
  - Two high momentum isolated leptons of the same charge
  - Large missing E_T
- Backgrounds:
  - physical: WZ/ZZ
  - instrumental: charge flips,multijet
- Estimation of background composition
  - ee/μμ: fit invariant mass of two leptons Mjj to a weighted sum of distributions for WZ.ZZ,charge flips and multijet
  - eμ:obtain track probability from ee/μμ , then multiply by the number of unlike sign events to get the number of like sign events due to charge flips



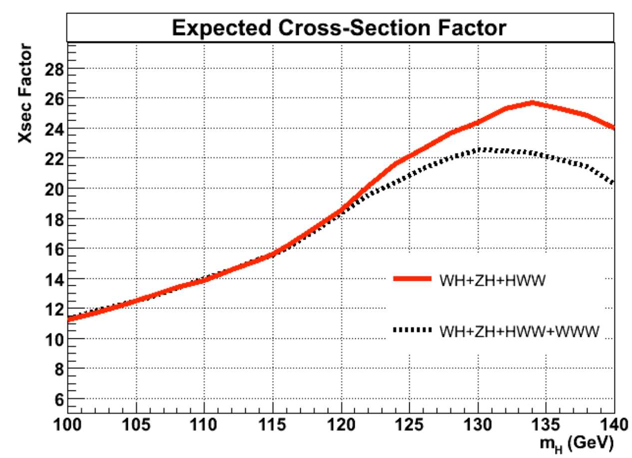
	ee	*eμ*	*μμ*
data	15	7	12
charge flips	8.73± 3.33	0.17± 0.05	7.38± 2.91
W/QCD	5.80± 2.92	4.38± 0.26	3.11± 2.10
WZ	0.77± 0.08	2.11± 0.25	1.77± 0.25
ZZ	0.13± 0.01	0.31± 0.03	0.21± 0.03
total	15.43± 3.93	6.97± 0.37	12.47± 3.50

$WH \rightarrow WWW^* \rightarrow l^{\pm}\nu l^{\pm\prime}\nu' + X$ (2 like-sign leptons)

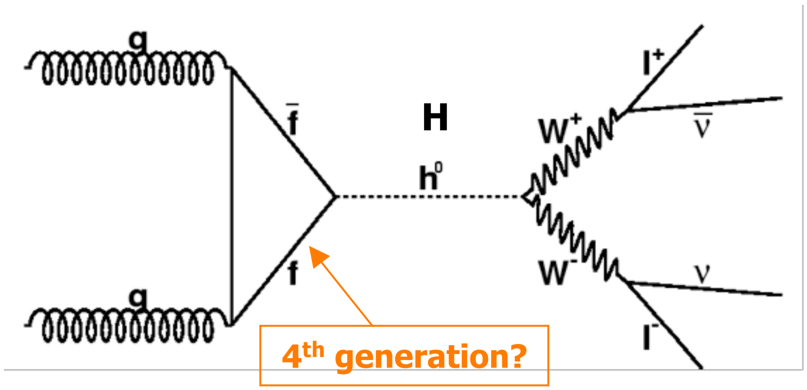
M_H (GeV)	115	135	155	175
Charge flips	2.35±0.90	1.40±0.53	1.12±0.43	0.89±0.31
QCD	2.35±1.04	2.04±0.83	1.64±0.69	1.16±0.46
WZ	3.40±0.28	1.87±0.15	1.51±0.12	1.26±0.10
ZZ	0.34±0.03	0.21±0.02	0.17±0.01	0.15±0.01
Total	8.44±1.37	5.52±0.99	4.45±0.82	3.46±0.57
Signal	0.037±0.004	0.100±0.010	0.143±0.015	0.110±0.011
Data	9	6	6	6



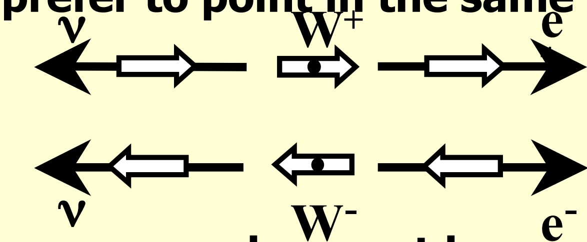
Effect on global combination significant in the intermediate region (125-145 GeV)



SM "Heavy" Higgs: H → WW* → lνlν



Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW comes from spin 0 Higgs:
leptons prefer to point in the same direction.

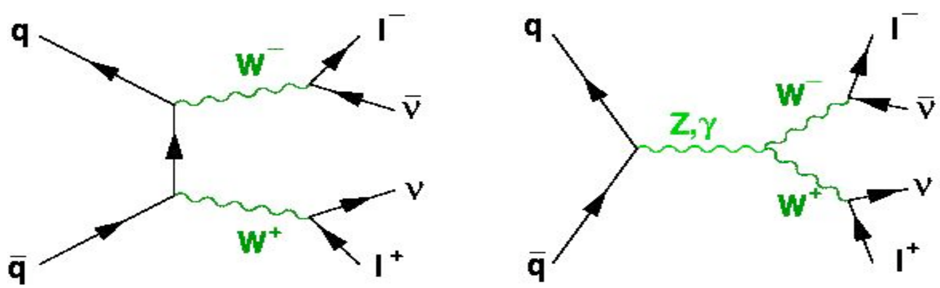


But Higgs mass peak cannot be reconstructed due to the presence of 2 ν→ look for an excess

CDF and DØ already published on 0.3-0.4 fb^{-1}

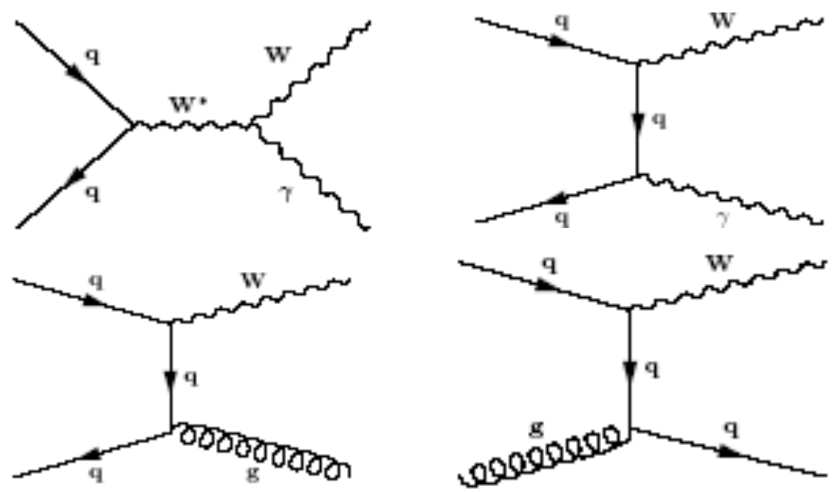
Major backgrounds

WW production



Now measured at the Tevatron by both expts. in agreement with NLO calculation:12-13.5 pb

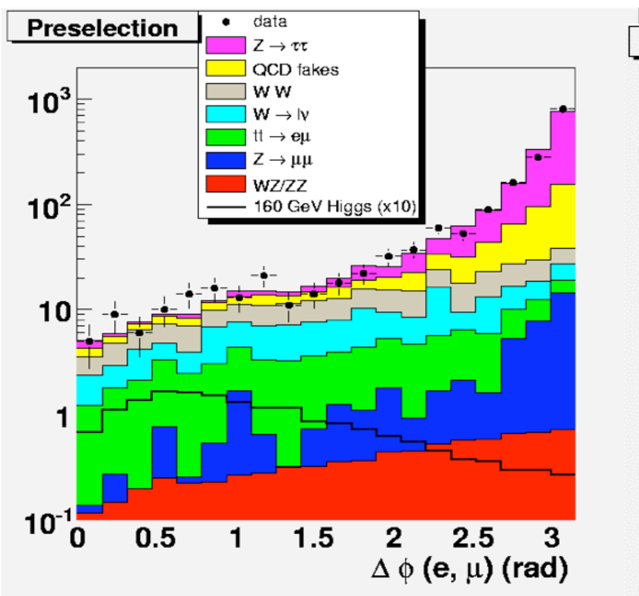
W + jet/γ production:

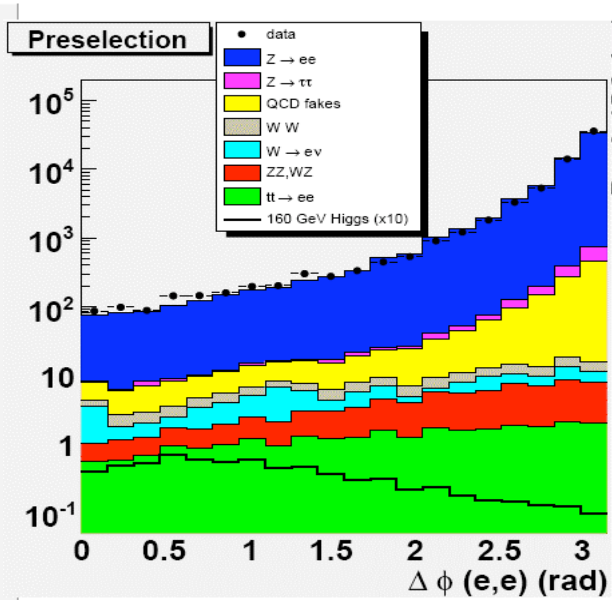


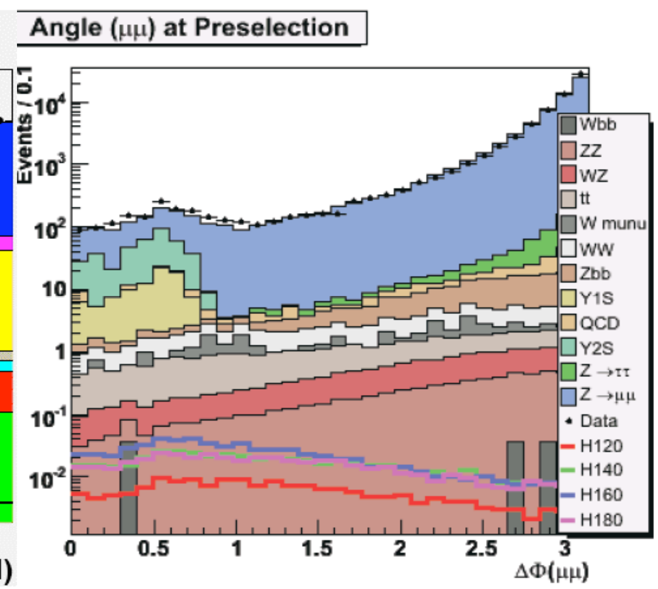
H → WW* → lνlν

Selection Strategy:

- **Presection:** lepton ID, trigger, opposite charge leptons
- **Remove Multijet and Z→l^+l^-:** $\not\!\!E_T$ > 20 GeV
- **Reject events with mismeasured jet energy**
- **Higgs Mass Dependent Cuts:** Invariant Mass (M_{l+l-}); Min. Transverse Mass
  Sum of lepton p_T^l and $\not\!\!E_T$ ($\Sigma\, p_T^l + \not\!\!E_T$)
- **Anti tt(bar) cut:** $H_T = \Sigma\, P_T^{jet} < 100$ GeV
- **Spin correlation in WW pair:** $\Delta\phi(l,l) < 2.0$



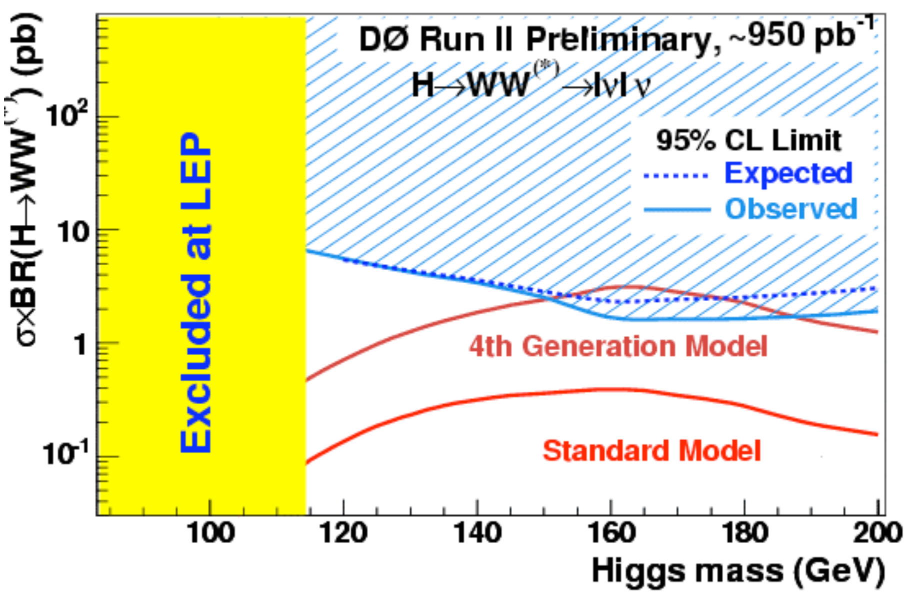




$H \rightarrow WW^* \rightarrow l\nu l\nu$

Expected/Observed # of events for m_H = 160 GeV (L ~ 950 pb^{-1}):

	Data	Sum BG	WW	W+jet/γ	Z/γ	top	WZ/ZZ	Multijet	H→WW*
e,e	10	10.3±0.6	7.0±0.2	1.4±0.6	0.0±0.0	1.1±0.1	0.8±0.1	0.06±0.02	0.415
e,μ	18	24.4±1.5	16.4±0.1	5.3±1.5	0.02±0.01	2.1±0.1	0.6±0.1	0.1±0.05	0.97
μ,μ	9	9.8±0.8	6.6±0.1	1.0±0.4	0.6±0.4	0.5±0.1	0.5±0.1	0.6±0.6	0.35



SM only a factor 4 away

We exclude 4th generation models, for which m_H=150-185 GeV

Combining Higgs boson Searches

CDF uses a Bayesian approach

- Use Bayesian posterior probability
- Assume flat prior density for the number of Higgs events

- Combined Binned Poisson Likelihood:

$$\mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) = \prod_{i=1}^{N_C} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} / n_{ij}!$$

- Combined Posterior Density Function:

$$p(R|\vec{n}) = \int d\vec{s} \int d\vec{b} \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) \times s_{tot} / \int dR \int d\vec{s} \int d\vec{b} \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) \times s_{tot}$$

DØ uses the CLs (LEP) Method

the CL_S confidence interval is a normalization of CL_{S+B}

CL_{S+B} = signal + bkgd hypothesis, CL_B = bkgd only hypothesis

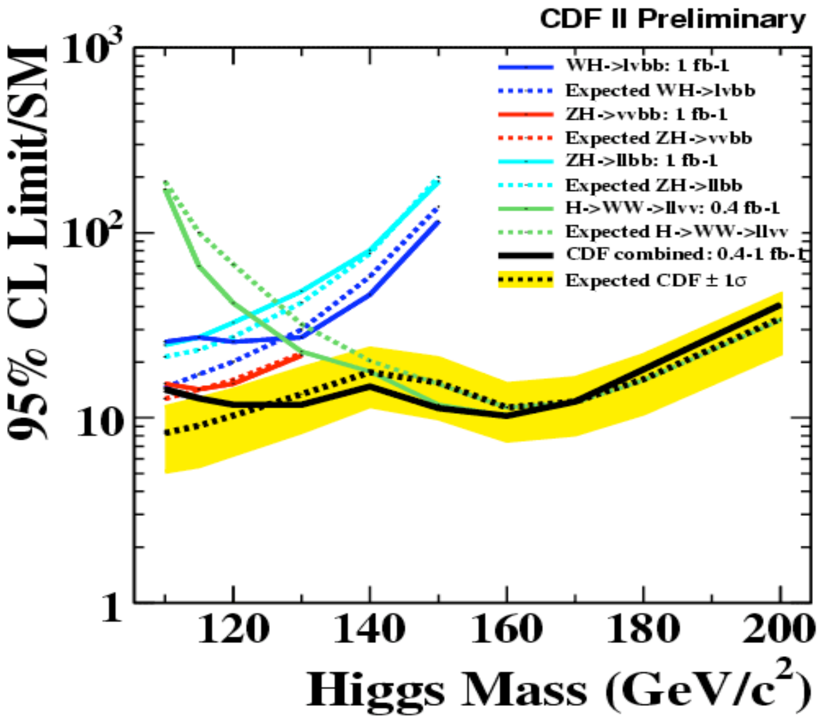
$CL_S = CL_{S+B}/CL_B$: CL_{S+B} & CL_B are defined using a "test statistic"

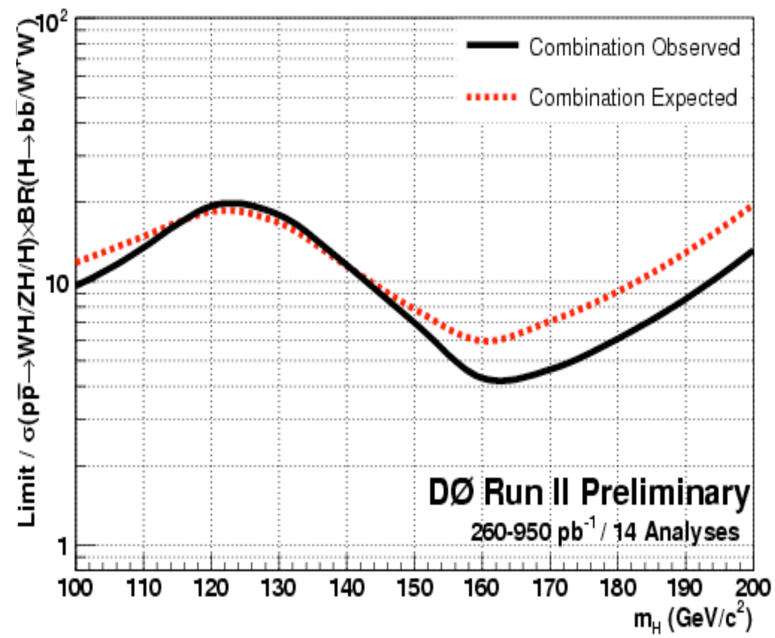
Test statistic used is the Log-Likelihood Ratio (LLR=-2 ln Q)

generated via Poisson statistics **($Q=e^{-(s+b)}(s+b)^d/e^{-b}b^d$) s,b,d=sig.,bkd,data)**

Tevatron Higgs combination is done with CLs and cross checked with Bayesian approach→ they give results compatible within 10%.

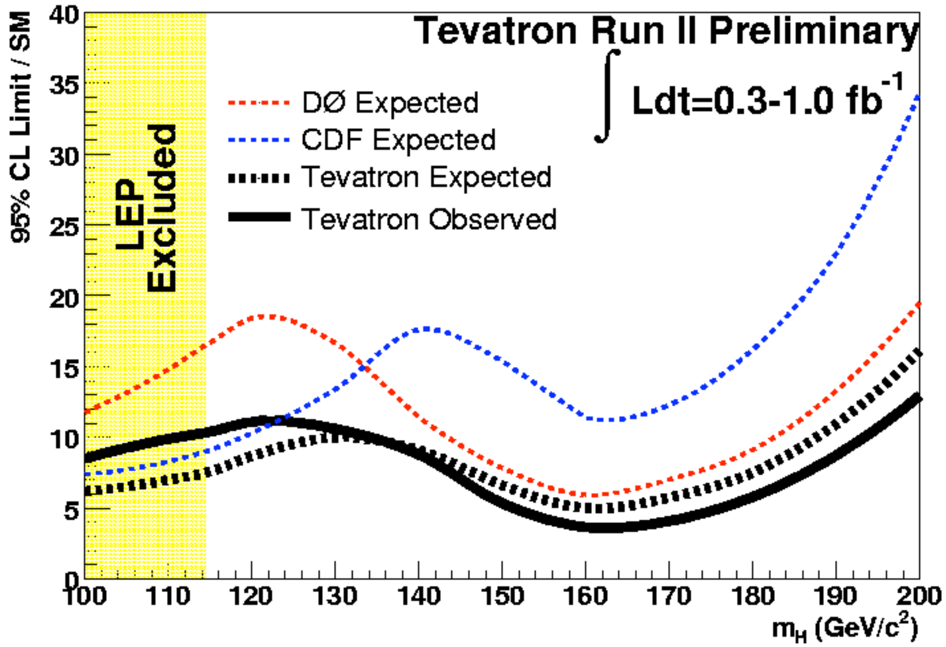
CDF & DØ SM Higgs Limits





- We present limits in terms of R=95% CL limit/σ_{SM}
- R≤1 indicates model exclusion

Tevatron SM Higgs Limits



- At the time of this combination,CDF added:
- $WH\rightarrow l\nu b\bar{b}$ / $ZH\rightarrow \nu\nu b\bar{b}$ / $ZH\rightarrow llb\bar{b}$ at 1 fb^{-1}
- DØ added: $H\rightarrow WW(ee,e\mu,\mu\mu)$ at 1 fb^{-1}
- Systematics very similar in size, most treated as uncorrelated between DØ and CDF
- R_{obs}:10.4 at m_H=115
  3.8 at m_H=160
- R_{exp}: 7.6 at m_H=115
  5.0 at m_H=160
- With asymmetric inputs(0.3-1.0 fb-1), we can extrapolate limits to 1 fb^{-1}:
  - R_{exp}: 6.0 at m_H=115
    4.0 at m_H=160

Sensitivity Prospects

- Advanced analysis techniques (NN,ME) provide factor of ~1.7 in equivalent luminosity
- New channels (taus,H→ZZ) will increase the sensitivity
- Many systematics currently limited with statistics

Ingredient (D0)	Equiv Lumi Gain@115	Xsec Factor m_H=115 GeV	Xsec Factor m_H=160 GeV
Today with 1fb-1	-	6.0	4.0
Lumi=2 fb-1	2	4.2	2.8
NN b-tagging	3	2.4	2.8
NN Analyses	1.7	1.9	2.1
Improved mass resolution	1.5	1.5	2.1
New Channels	1.3	1.3	1.8
Reduced systematics	1.2	1.2	1.7

R~1 when integrated lum ~3 fb^{-1} ~5.5 fb^{-1}

Conclusion

- At Tevatron, SM Higgs analyses are in very exciting time period
  - Increasing dataset (2 fb^{-1} now and expecting more data)
  - Better understanding background description
  - Both experiments understood detectors very well
  - More advanced analyses
- The combination limits of CDF and DØ are very encouraging

Tevatron is the best place for Higgs search right now and we are getting close to the sensitivity needed to have evidence for a light Higgs boson !!!

Backup

Systematic Uncertainties @ CDF

Channels	$l\nu b\bar{b}$		$\nu\bar{\nu}b\bar{b}$		$l^+l^-b\bar{b}$	W^+W^-
	Single	Double	Single	Double		
Acceptance						
Luminosity (%)	6.0	6.0	6.0	6.0	6.0	6.0
btag SF (%)	5.3	16.0	8.0	16.0	8	0.0
Lepton ID (%)	2.0	2.0	2.0	2.0	1.4	3.0
JES (%)	3.0	3.0	(1-20)	(1.6-20)	6.0	1.0
MC modeling (%)	4.0	10.0	4.0	5.0	2.0	5.0
Trigger (%)	0.0	0.0	3.0	3.0	0.0	0.0
Shapes (%)	0.0	0.0	0.0	0.0	-20.0	0.0
Backgrounds						
Mistag (%)	22	15	17	17	17	0.0
QCD (%)	17	20	-10	-44	-50	0
W/Z+HF(I) (%)	33	34	12	12	40	0
W+HF(II) (%)	0	0	-10	-42	0	0
Z+HF(II) (%)	0	0	-6	-19	0	0
Top(I) (%)	13.5	20	12	12	20	0
Top(II) (%)	0.	0.	-2	-3	0	0
Diboson(I) (%)	16	25	12	12	20	11
Diboson(II) (%)	0	0	-5	-10	0	0
Other (%)	0	0	0	0	0	-(12-18)

- The positive value means correlated, the negative value means uncorrelated
- The results seems insensitive to these correlations changing from 100% to 0%