Higgs Searches at Tevatron

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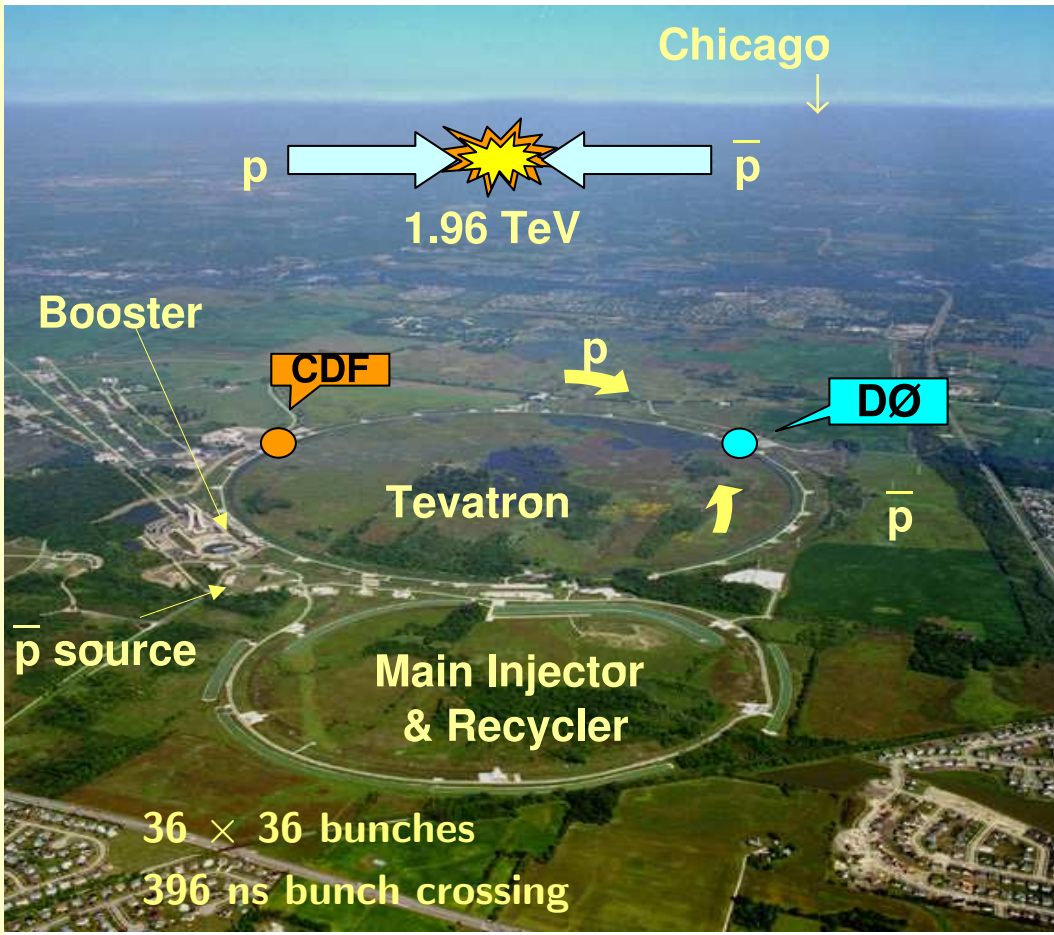
on behalf of the CDF and DØ collaborations

HCP 2006
Durham

Outline

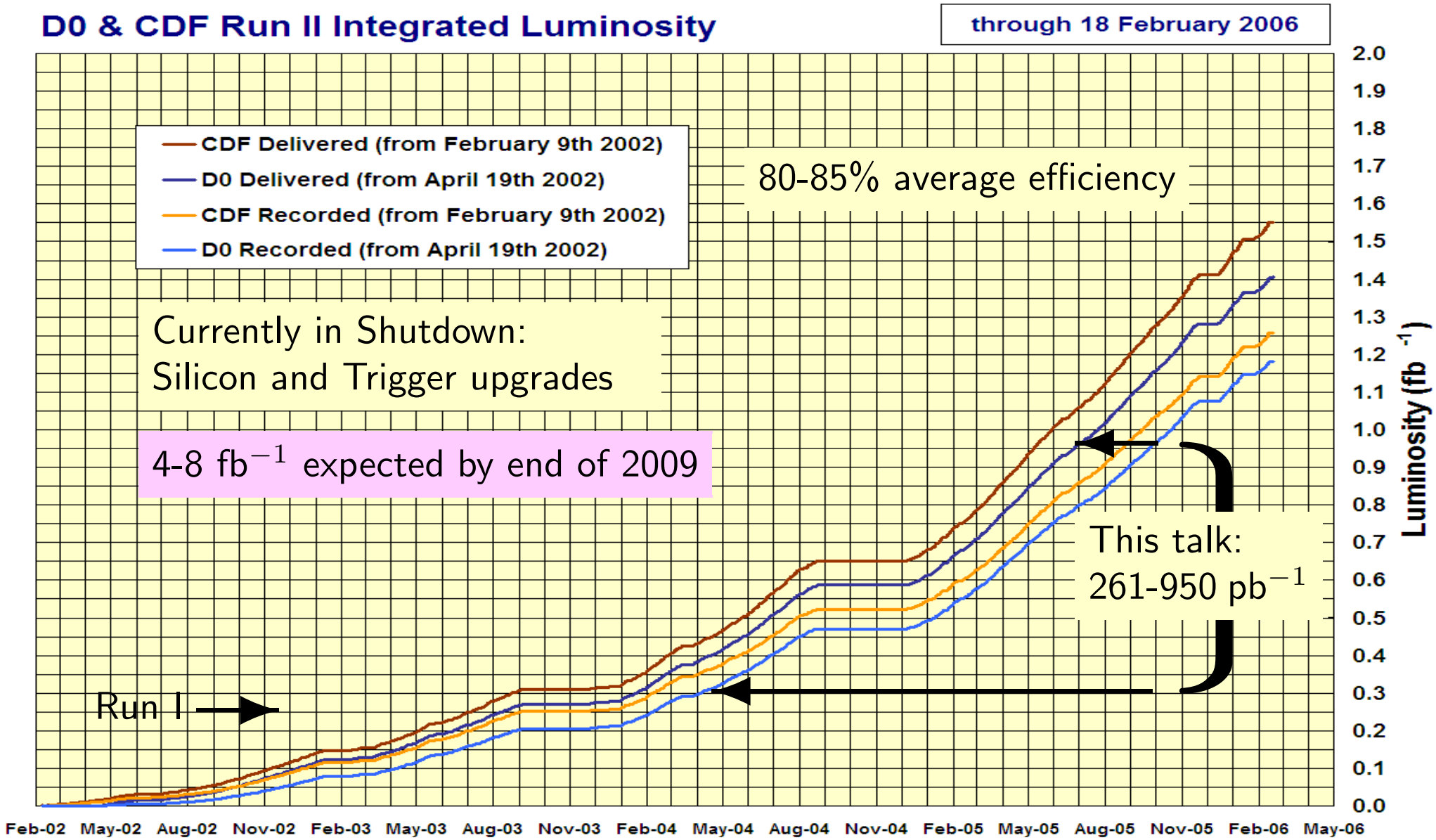
- Introduction
- SM Higgs $\rightarrow b\bar{b}$ (low mass)
  - $ZH \rightarrow \nu\nu b\bar{b}$
  - $WH \rightarrow \ell\nu b\bar{b}$
  - $t\bar{t}H \rightarrow \ell + 2q + 4b$
- SM Higgs $\rightarrow WW$ (high mass)
  - $WH \rightarrow WWW$
  - $H \rightarrow WW$
- Limits combination
- MSSM Higgs
  - Neutral Higgs $\rightarrow \tau\tau$
  - $t \rightarrow bH^+ \rightarrow \ell(+\tau)+$ jets



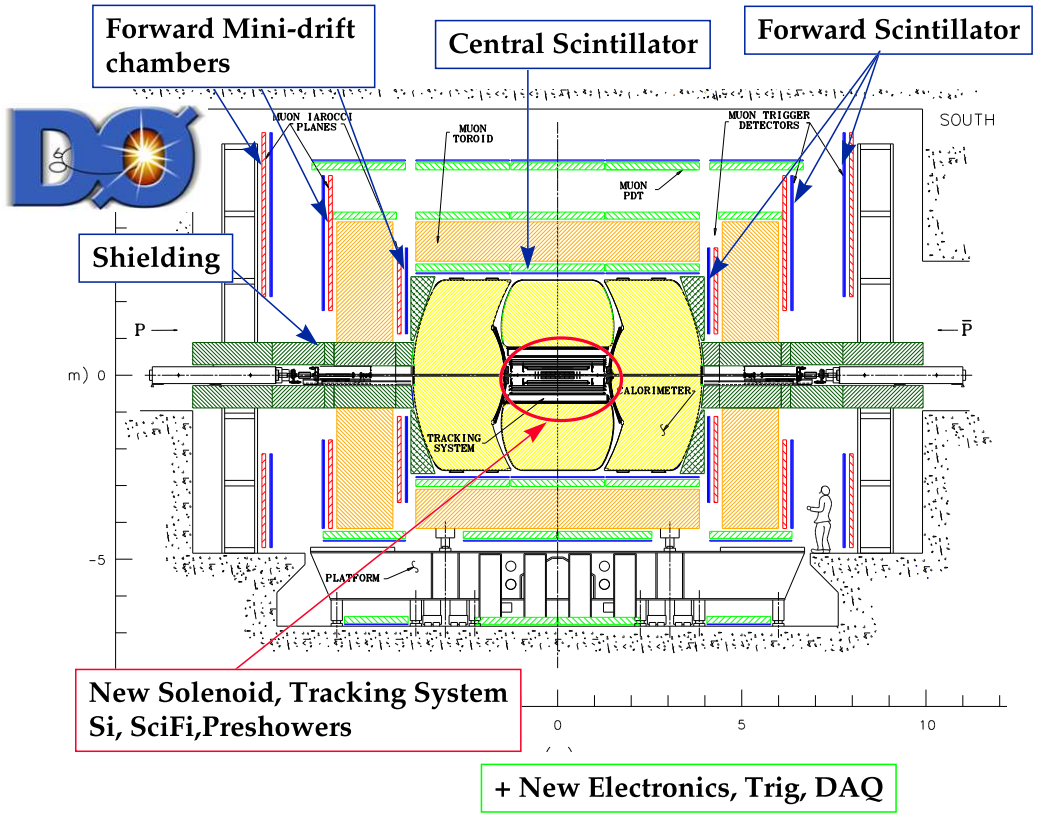
Only new results since last year's Moriond are shown

Thanks to all colleagues at the Tevatron for their contributions for this talk

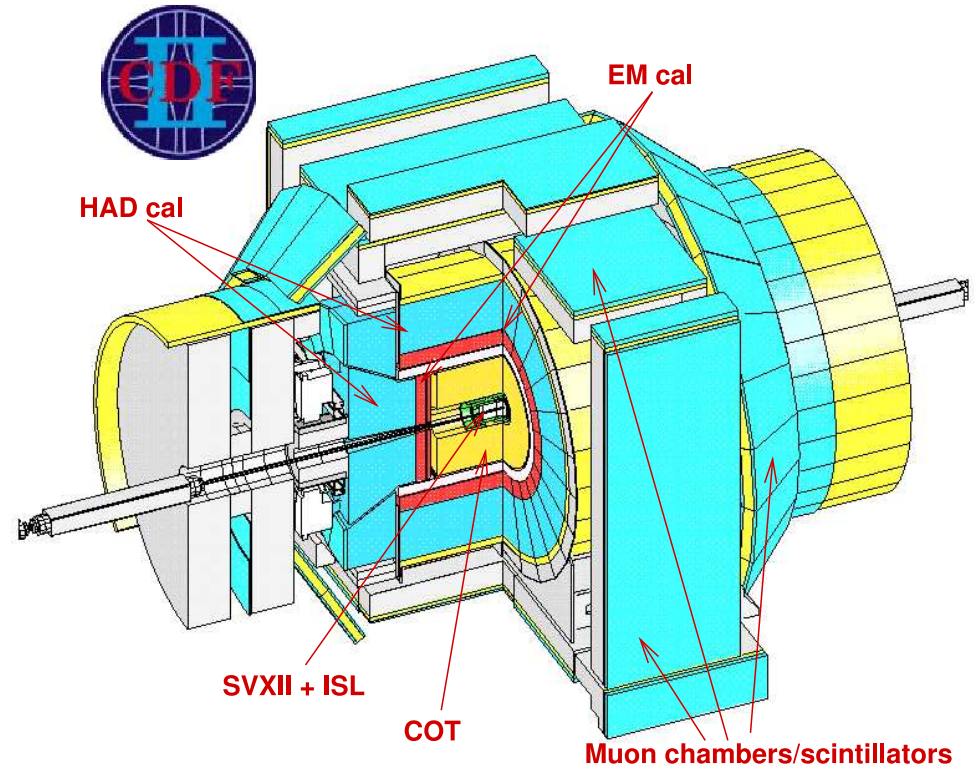
Tevatron Performance



DØ and CDF in Run II



+ New Electronics, Trig, DAQ



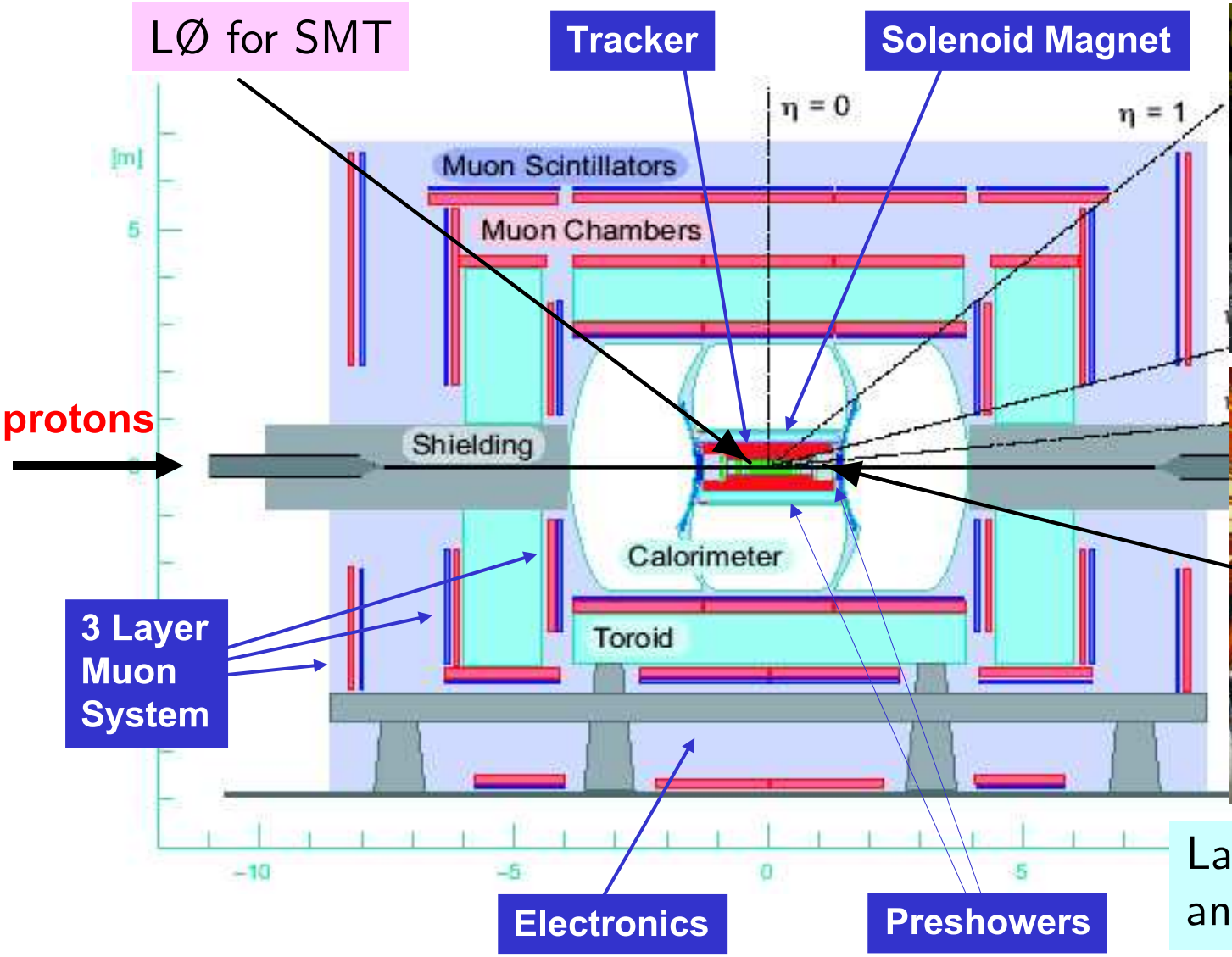
- Upgraded muon coverage
- New tracking system
- New silicon tracker + trigger
- New solenoid
- New preshowers

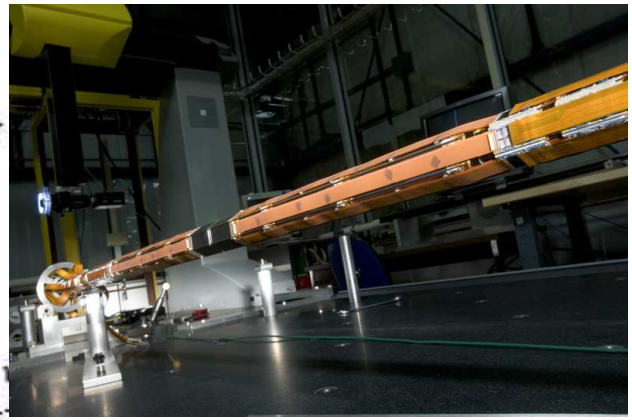
} Run IIa {

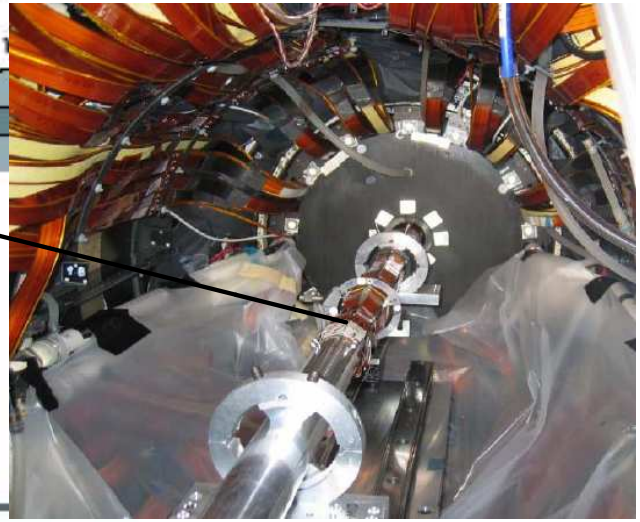
- Upgraded muon detectors
- New TOF detector
- New plug calorimeters
- New drift chamber
- New silicon tracker + trigger

Run IIb upgrades (Tracker, Calorimeter, Trigger) taking place

Layer Zero upgrade for DØ in Run IIb







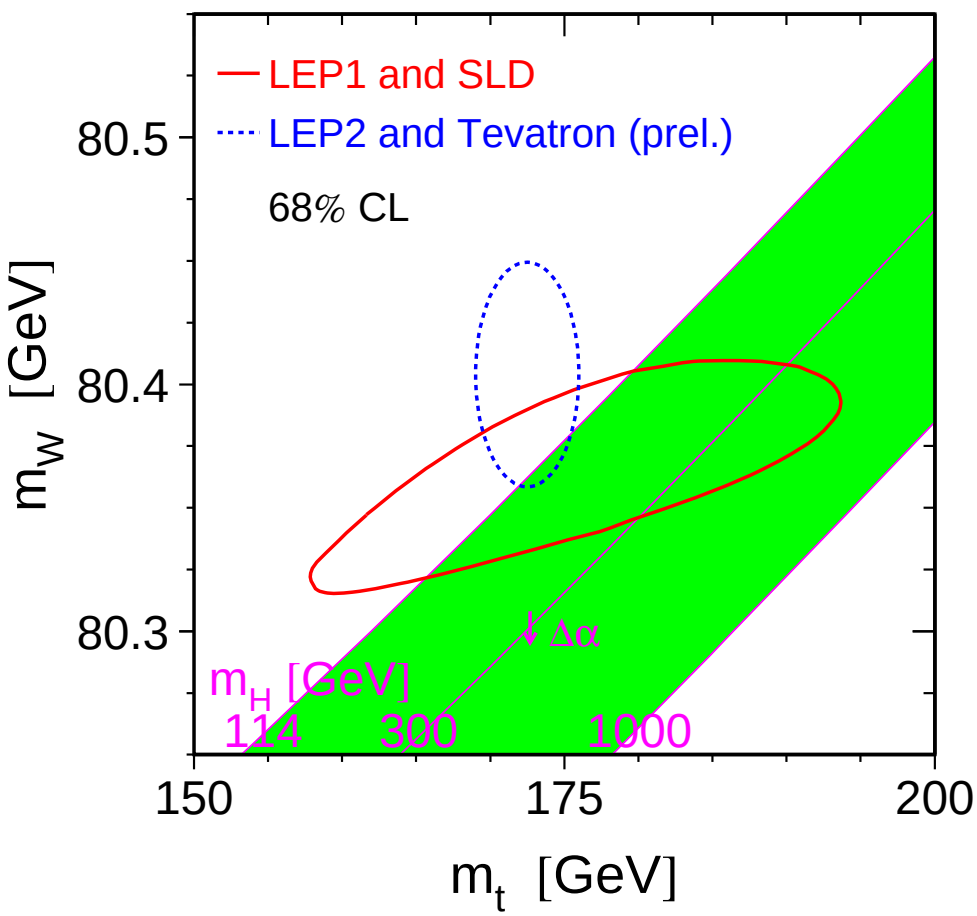
Layer 0 now inserted and fully read out

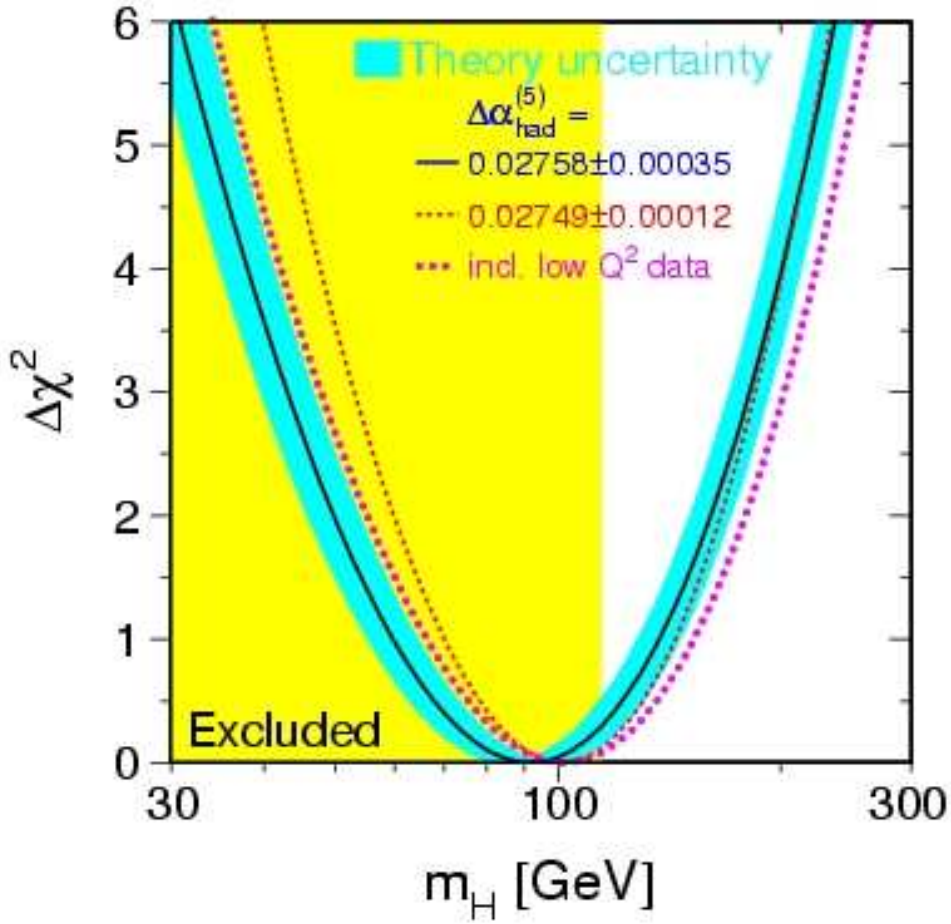
Excellent noise performance: S/N = 18

EW constraints on Higgs

m_H Constrains in the Standard Model

LEPEWWG 18/03/2006





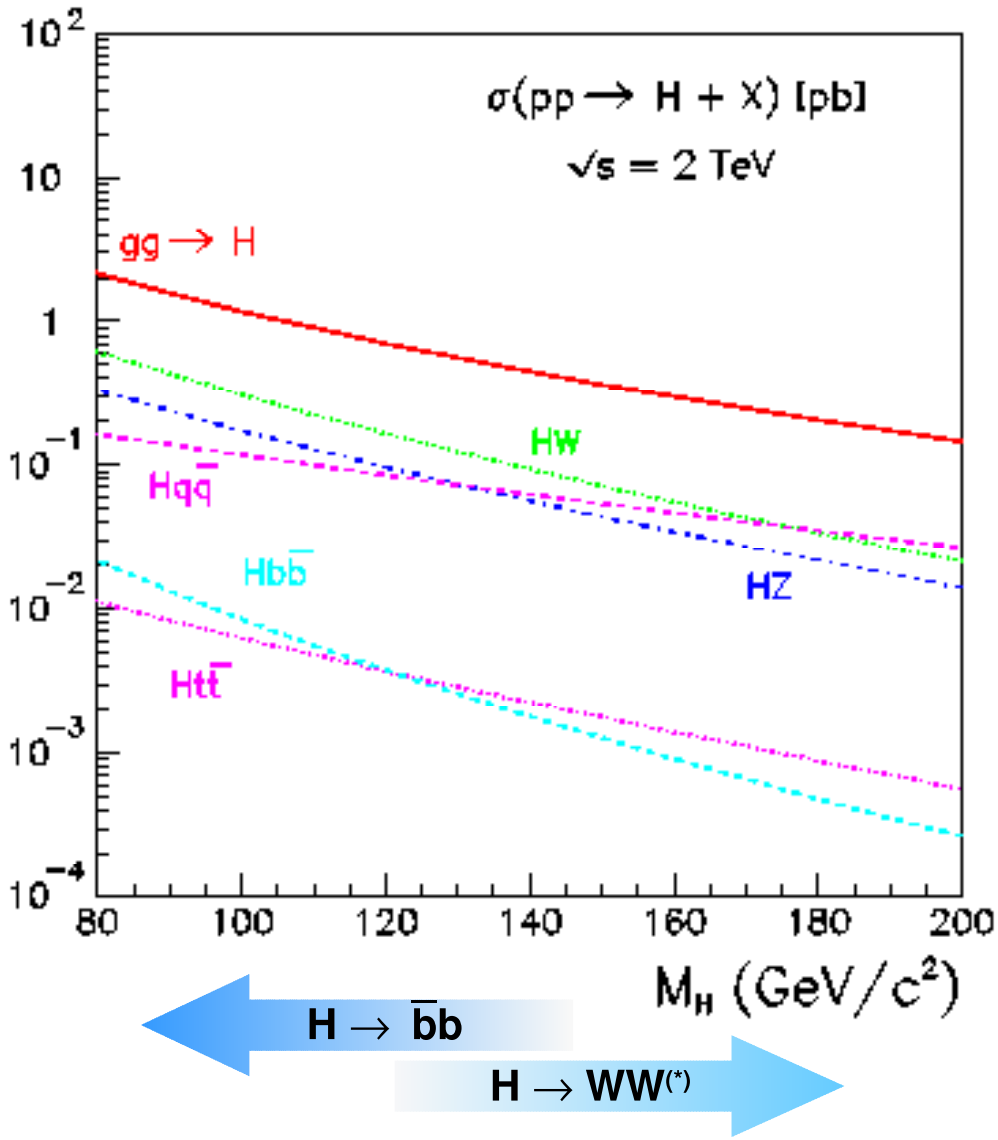
Direct Searches at LEP2:
$m_H > 114.4$ GeV @95%CL

$m_H < 175$ GeV @95%C (EW fit)
(< 207 GeV if LEP2 limit included)

A light Higgs is favoured

Standard Model Higgs Production

- Production cross sections are small: 0.1-1 pb depending on m_H, 1 in 10^{12} $p\bar{p}$ events is a Higgs
- $m_H < 135$ GeV: decay into $b\bar{b}$: $gg \to H \to b\bar{b}$ overwhelmed by multijet (QCD) background
  - Searches can be performed in W/H associated production with lower background
  - Best channels: $WH \to \ell\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$
- $m_H > 135$ GeV: decay into WW: $gg \to H \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$ $WH \to WWW^{(*)}$ final states can be explored



Dominant decay modes

If light SM Higgs we have already some in our data

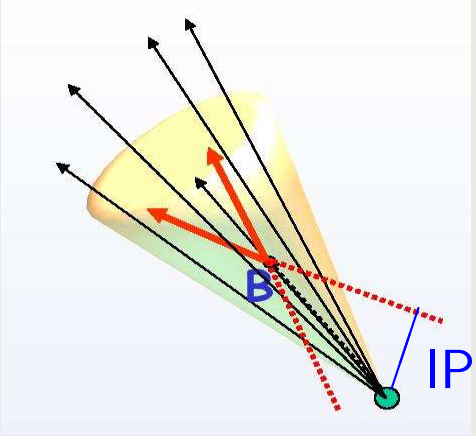
Backgrounds and Tools

Understanding and modeling of background is crucial

- In particular for advanced analysis techniques
- Electroweak Backgrounds (W, Z, WZ, WW, Top):
  - Monte Carlo distributions normalized to (N)NLO cross sections
- Multijet (QCD) and instrumental background taken from real data control samples

Measurements also rely on:

- Jet reconstruction
- b-Tagging:
  - Based on Track Impact Parameter (IP) measurements or Secondary Vertex reconstruction



- Lepton identification
- Missing transverse energy

Both, DØ and CDF detectors provide the excellent performance needed

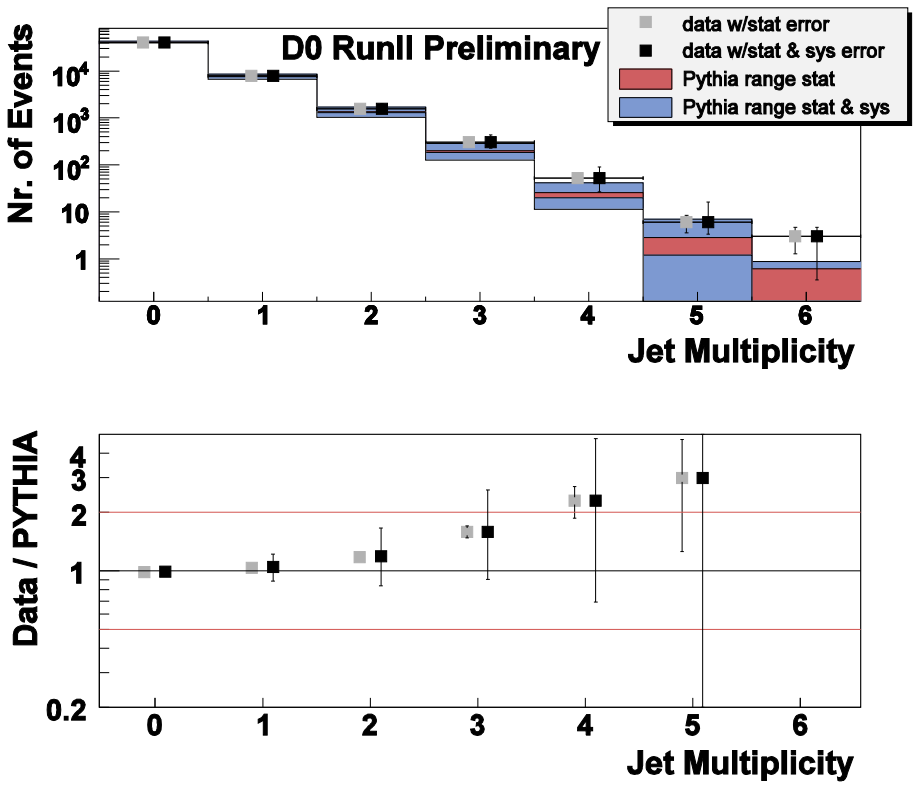
First check understanding of background

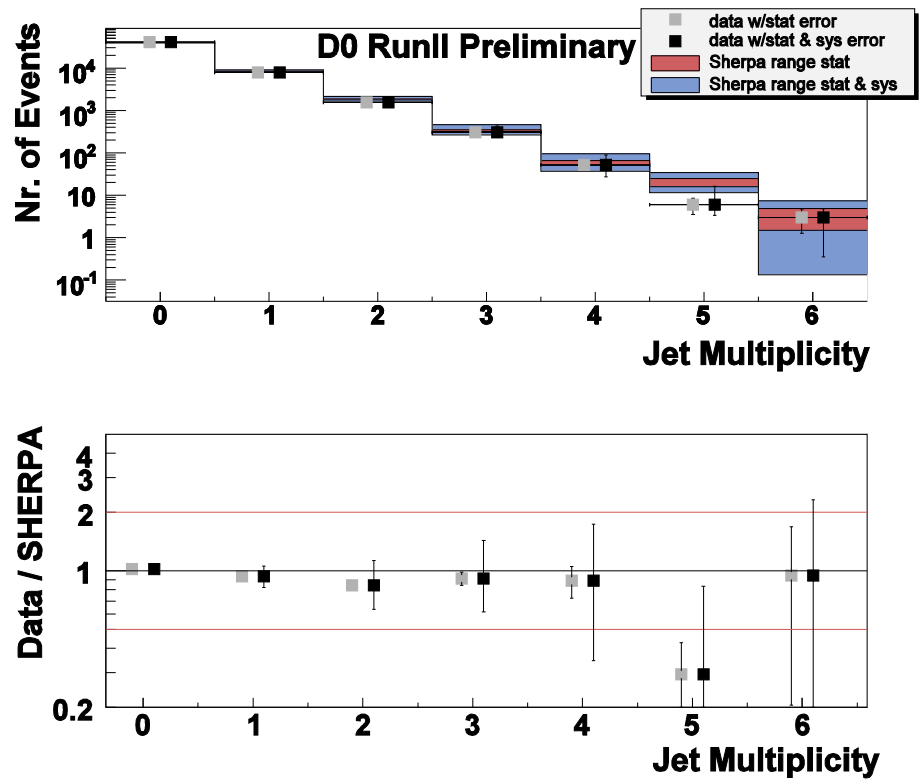
$Z/\gamma^* \to ee+$ jets

- Understanding and rejection of background is crucial
- Comparison of jet multiplicities and distributions in data and MC
  - PYTHIA 6.319 vs. Sherpa 1.0.6
  - Sherpa: Matrix element + parton showers using CKKW matching algorithm

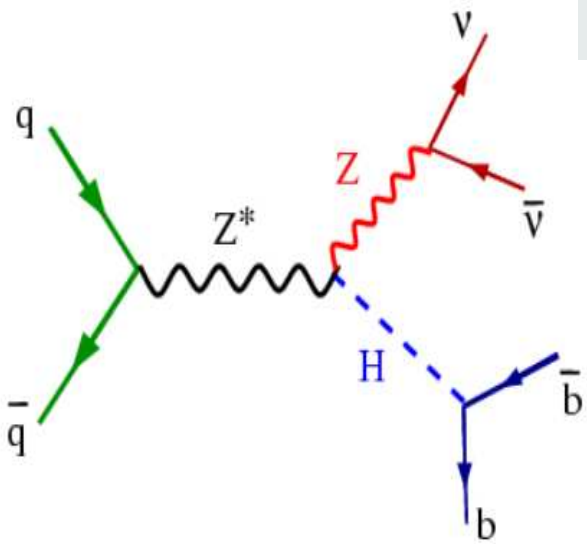
- Event selection includes:
  - Electron p_T>25 GeV, $|\eta|$<2.5/1.1
  - p_T(jets)>15 GeV
  - 70 GeV $< m_{ee} <$ 120 GeV

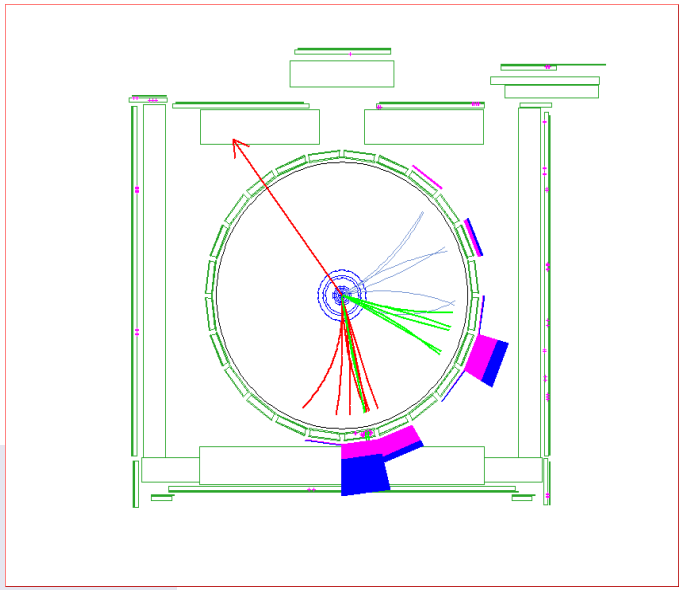
Sherpa agrees well with data up to $N_{\text{jet}} = 4$



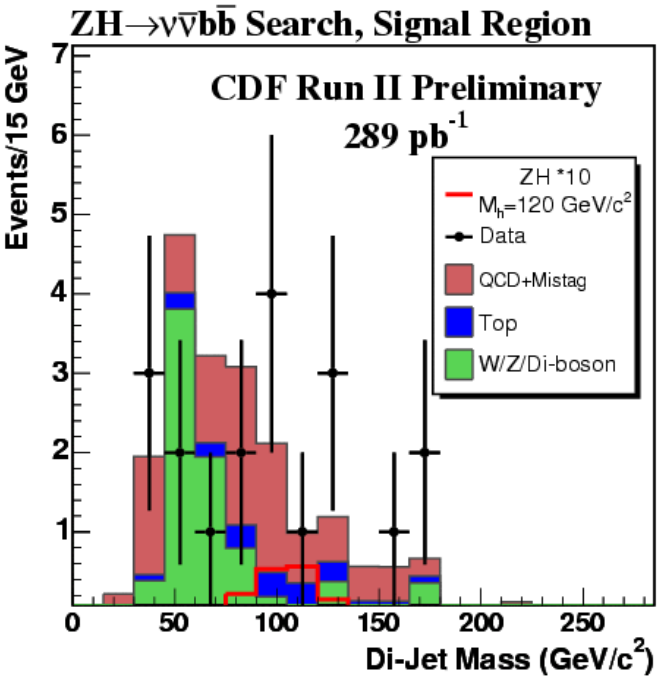


$ZH \rightarrow \nu\bar{\nu}b\bar{b}$





$E_{T,jj} = 54.7$ GeV
$\not{E}_T = 144.8$ GeV
$m_{jj} = 82.1$ GeV



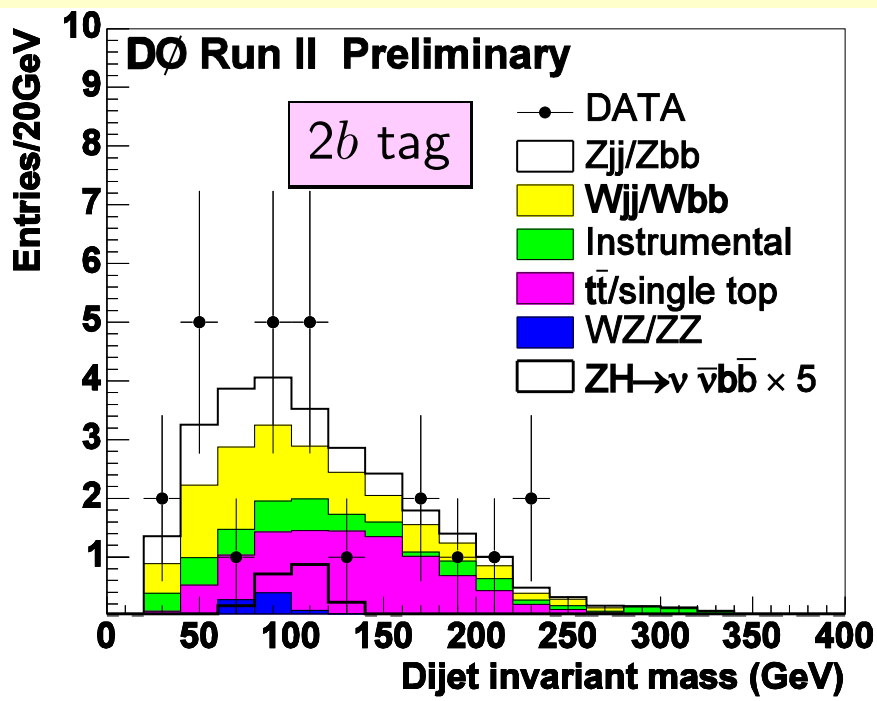
- Event selection includes:
  - ≥ 1 tagged b-jet
  - 2 jets with E_T >60/25 GeV
  - $\not{E}_T > 70$ GeV
- Backgrounds:
  - W/Z + heavy flavour jets
  - Multijets (QCD)
  - Di-bosons
  - Mis-tagged b-jets
  - Top pairs

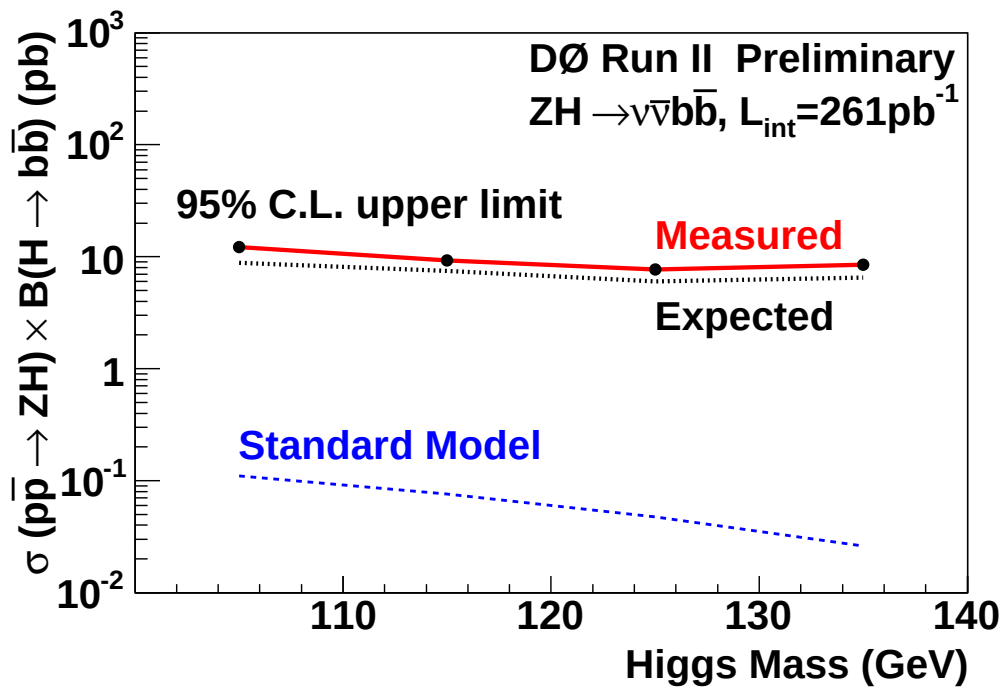
- $m_H = 120$ GeV, $80 < m_{jj} < 120$ GeV
  - 6 events observed
  - 4.36 $\pm$ 1.02 predicted
  - $\sigma_{95} = 4.5$ pb

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

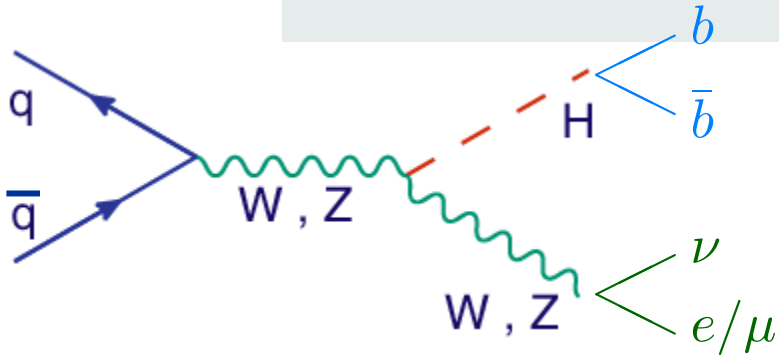
- Improved event selection includes:
  - 2 Acoplanar jets with $E_T > 20$ GeV
  - $\not\!\!E_T > 50$ GeV
  - Sum of scalar jet $E_T < 240$ GeV
- Separate analysis for single and double b-tagged events, combined later:
  - Increased statistics

- $m_H = 115$ GeV, $75 < m_{jj} < 125$ GeV:
  - 11 events observed
  - 9.4 $\pm$ 1.8 predicted
  - $\sigma_{95} = 4.3$ pb
- Using this analysis, limits on WH with missed lepton can be placed
  $\Rightarrow$ Improves combined limit on WH

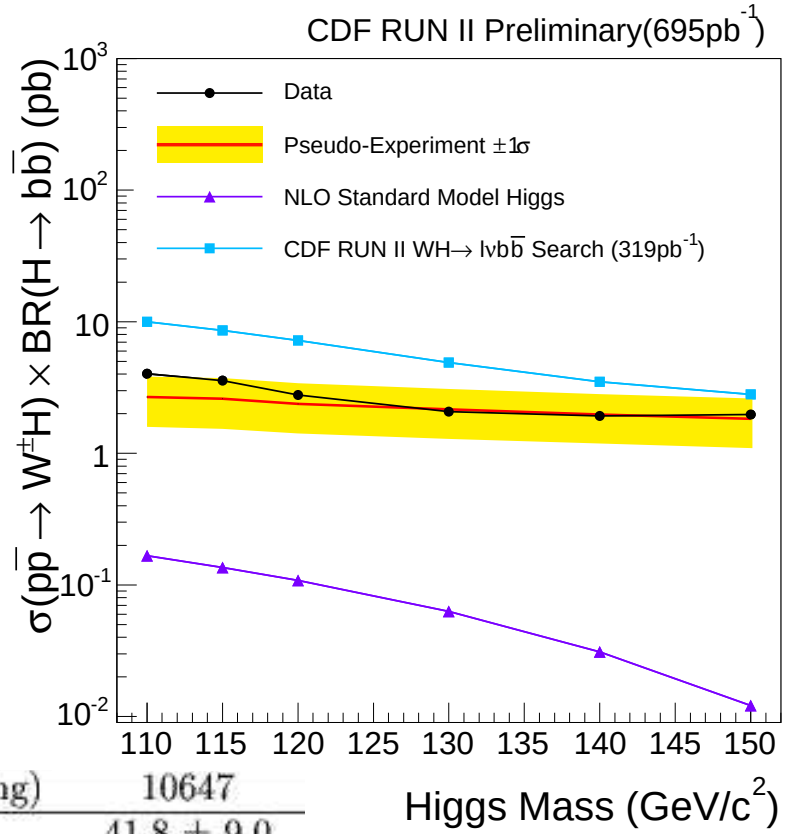


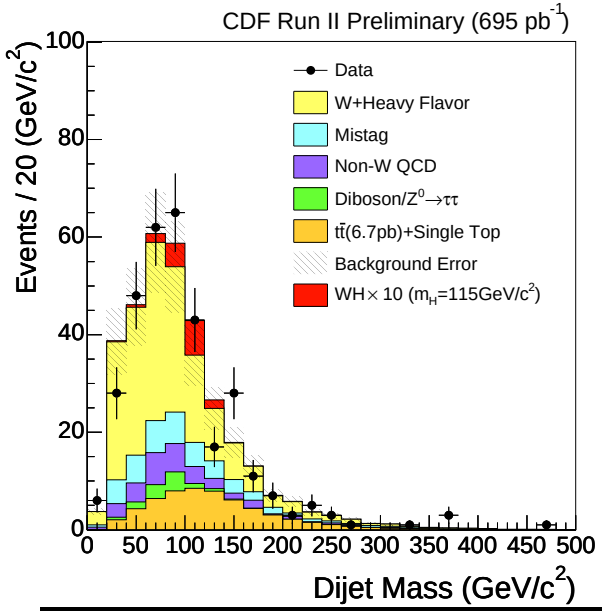


$WH \rightarrow \ell\nu b\bar{b}, \ell = e, \mu$



- Muon and electron channel combined:
  - Separate analysis for single and double b-tagged events (NN b-tagger)
  - p_T(jets)> 15 GeV
  - Electron or muon with p_T >20 GeV
  - $\not{E}_T > 20$ GeV





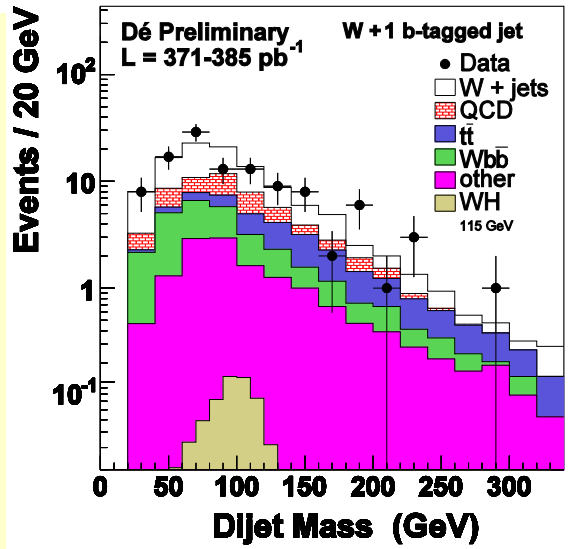
Observed Events(Before b-tagging)	10647
Mistag	41.8 ± 9.0
$Wb\bar{b}$	120.2 ± 41.1
$Wc\bar{c}$	33.7 ± 11.5
Wc	25.0 ± 6.5
$t\bar{t}$(6.7pb)	37.8 ± 6.4
Single Top	20.1 ± 2.1
Diboson/$Z^0 \rightarrow \tau\tau$	10.6 ± 1.7
non-W QCD	29.5 ± 5.1
Total Background	318.8 ± 54.7
Observed Events($\geq$1tag w/ NNtag)	332

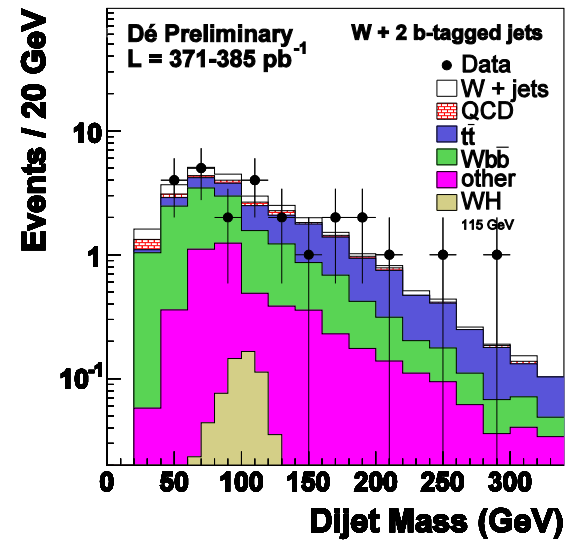
$WH \to \ell\nu b\bar{b}, \ell = e, \mu$

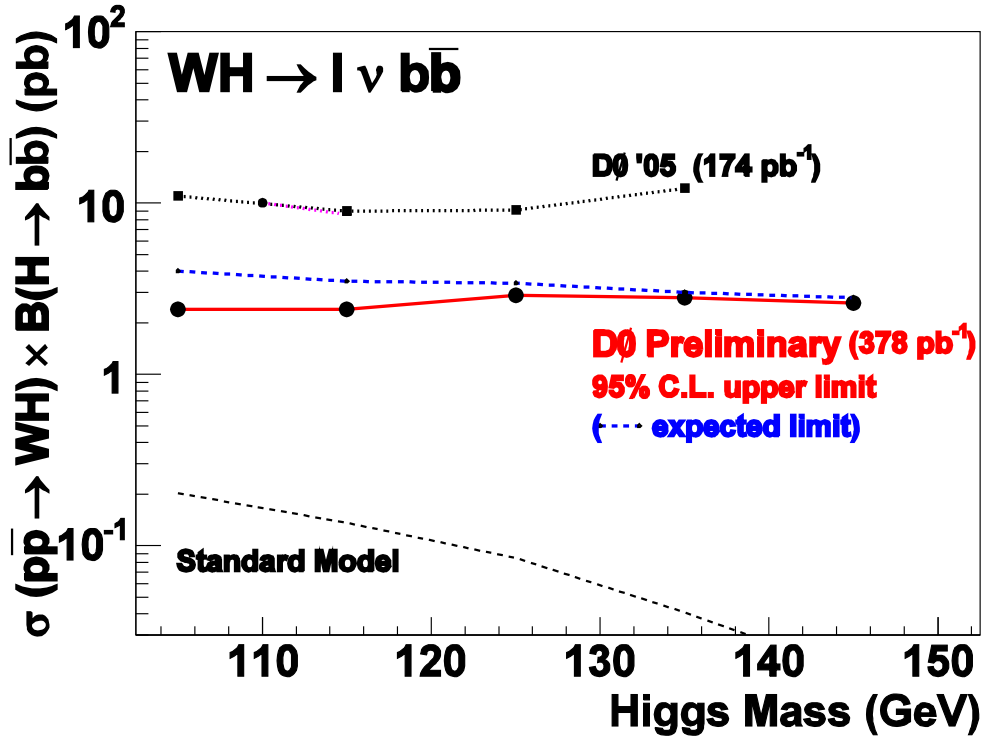
- New muon analysis
- Re-optimized electron analysis
- Separate single and double b tag analyses
- Event selection includes:
  - Central isolated e/μ
  - $\not\!\!E_T > 25$ GeV
  - 2 jets:
    $E_T > 20$ GeV, $|\eta| < 2.5$
    one or two tagged b jets
- Limit from combined channels:
  - $m_H = 115$ GeV, $75 < m_{jj} < 125$ GeV

events	single tag	double tag
observed	32	6
predicted	45	9.3

$*$ $\sigma_{95} = 2.5$ pb





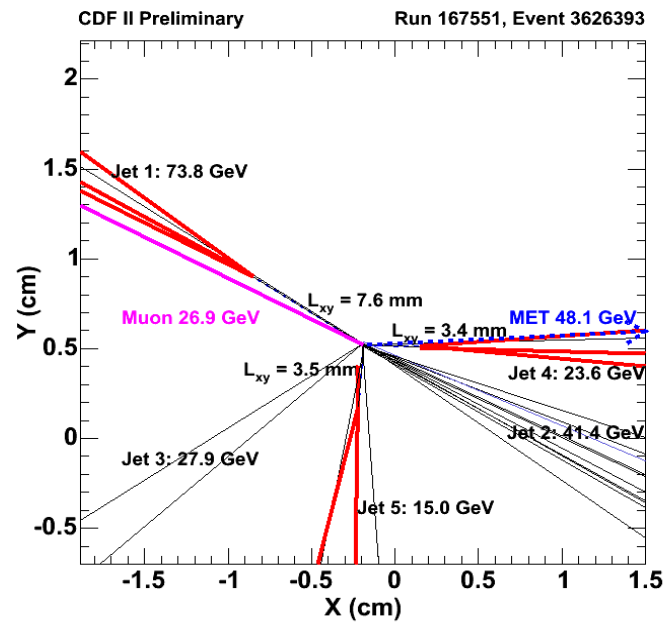


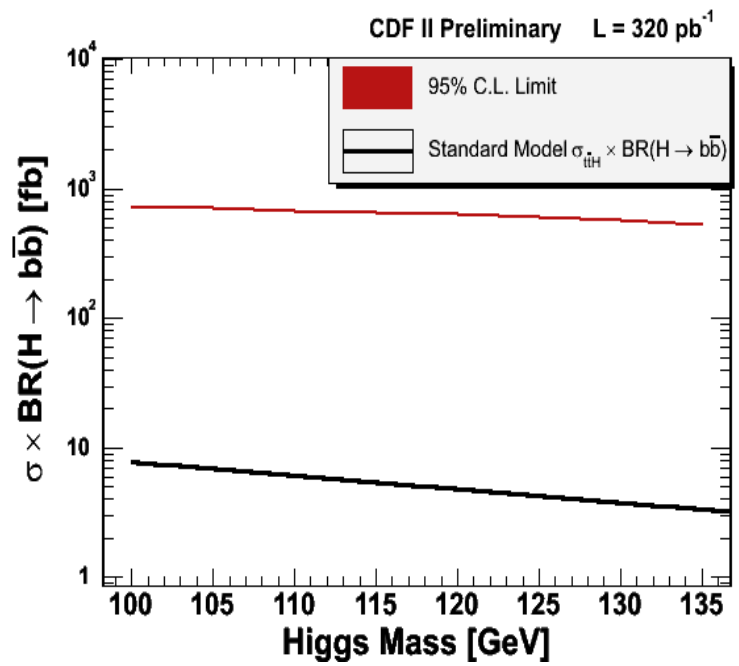
$t\bar{t}H \rightarrow \ell + 2q + 4b$

- Look for final state with $WWbbbb$:
  - Exactly one identified e or μ
  - 5 more jets, $p_T > 15$ GeV
  - $\not\!\!E_T > 25$ GeV
  - At least 3 jets b-tagged

Source	Yield
Mistag	0.49±0.010
Irreducible	0.36±0.07
Multi-Jet (QCD)	0.04±0.04
Total Background	0.89±0.12
Signal ($m_H = 115$ GeV)	0.024±0.005
Observed	1

- Limit (for $\sigma \times \mathrm{BR}(H \rightarrow b\bar{b})$)
  - $m_H = 115$ GeV
    $\sigma_{95} = 0.66$ pb



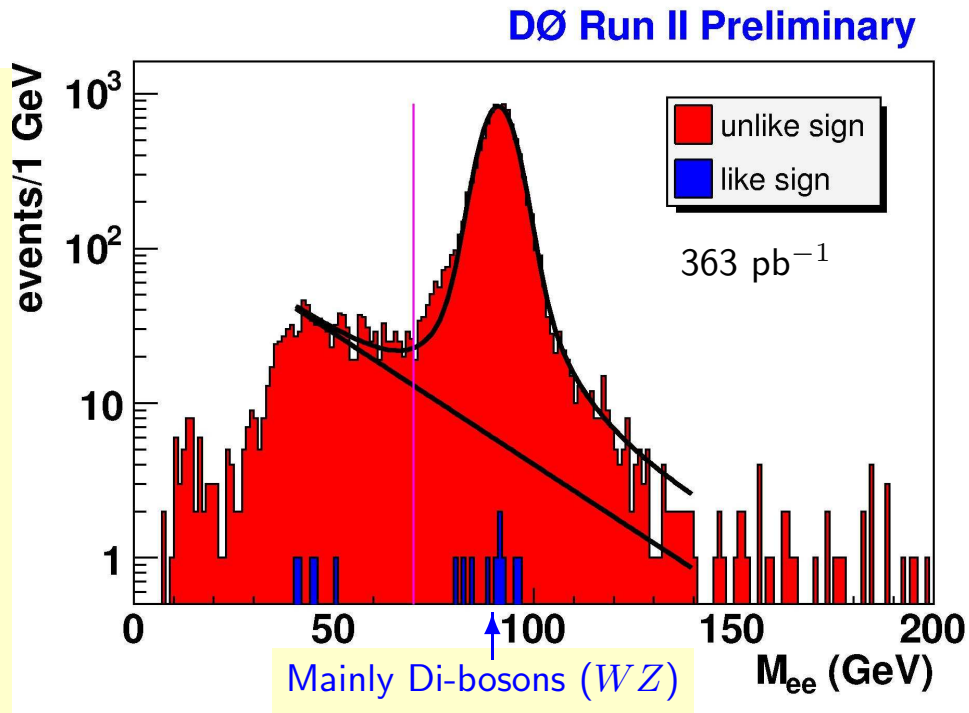


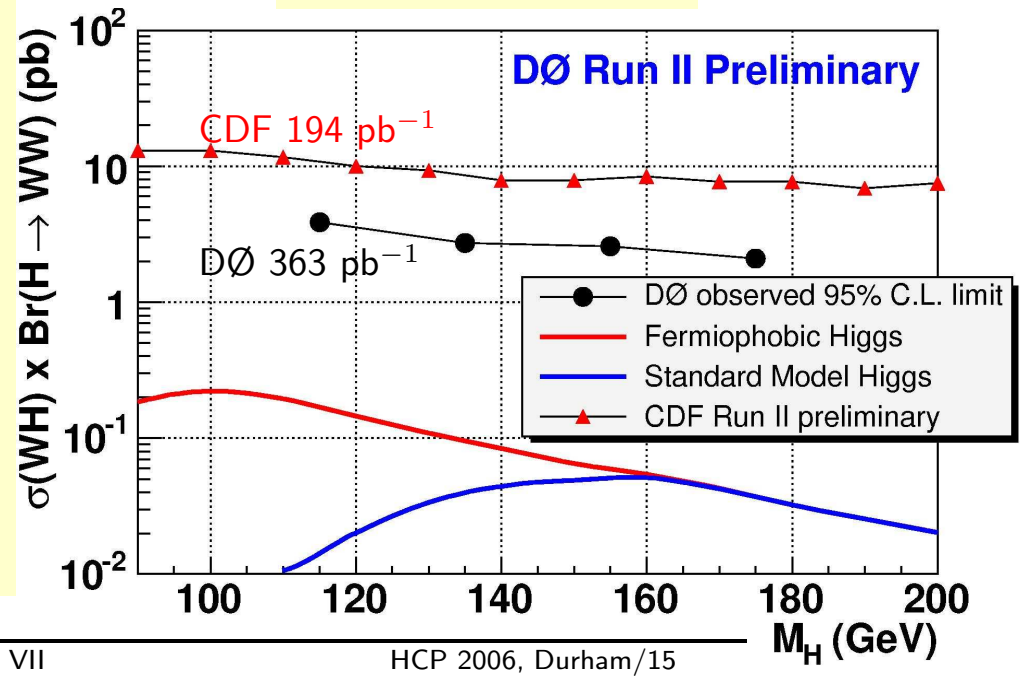
$WH \to WWW^{(*)} \to \ell^{\pm}\ell^{\pm} + X$

- Event selection includes:
  - 2 isolated like sign leptons $(ee, e\mu, \mu\mu)$
  - $p_T(\ell) > 15$ GeV
  - $\not{E}_T > 20$ GeV

	observed	expected
ee	1	0.70 ± 0.08
$e\mu$	3	4.32 ± 0.23
$\mu\mu$	2	3.72 ± 0.75

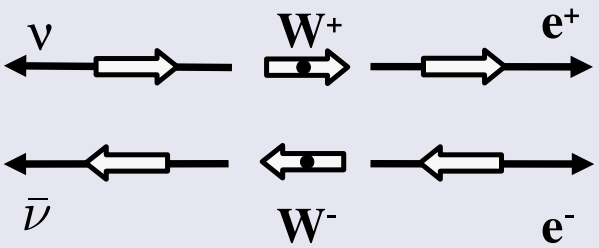
- Limit:
  - $\sigma_{95} = 3.88$ pb



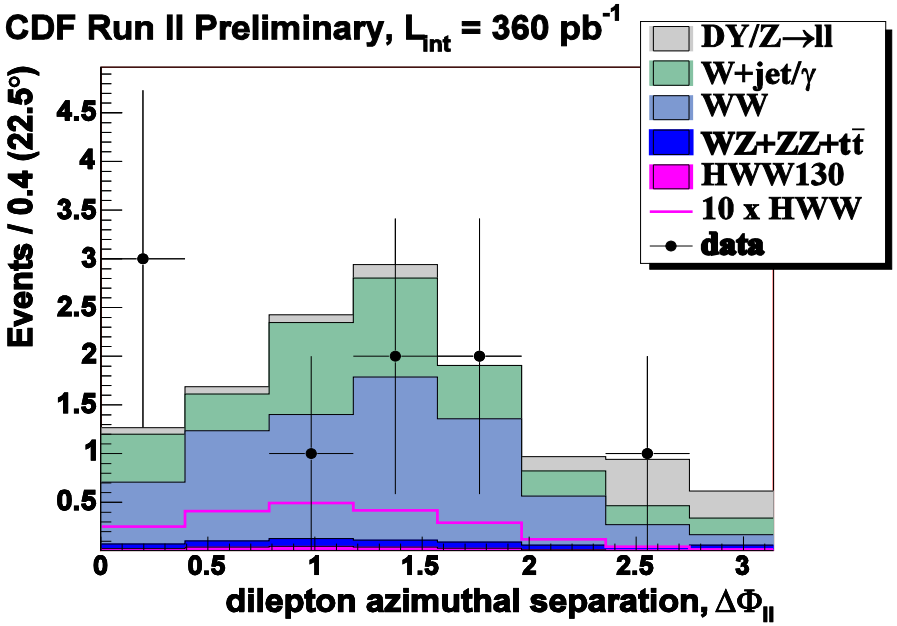


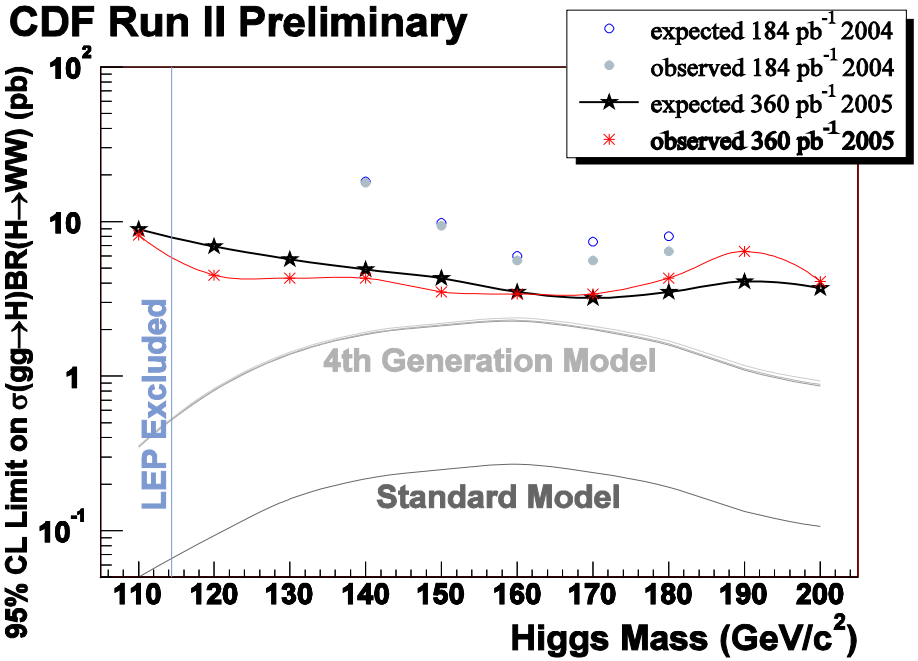
$H \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\bar{\nu}, \ell = e, \mu$

- Higgs mass reconstruction not possible due to two neutrinos
- Exploit spin correlation to supress background
  - $\Delta\Phi(\ell\ell)$ is particulary usefull
  - Charged leptons from Higgs are collinear



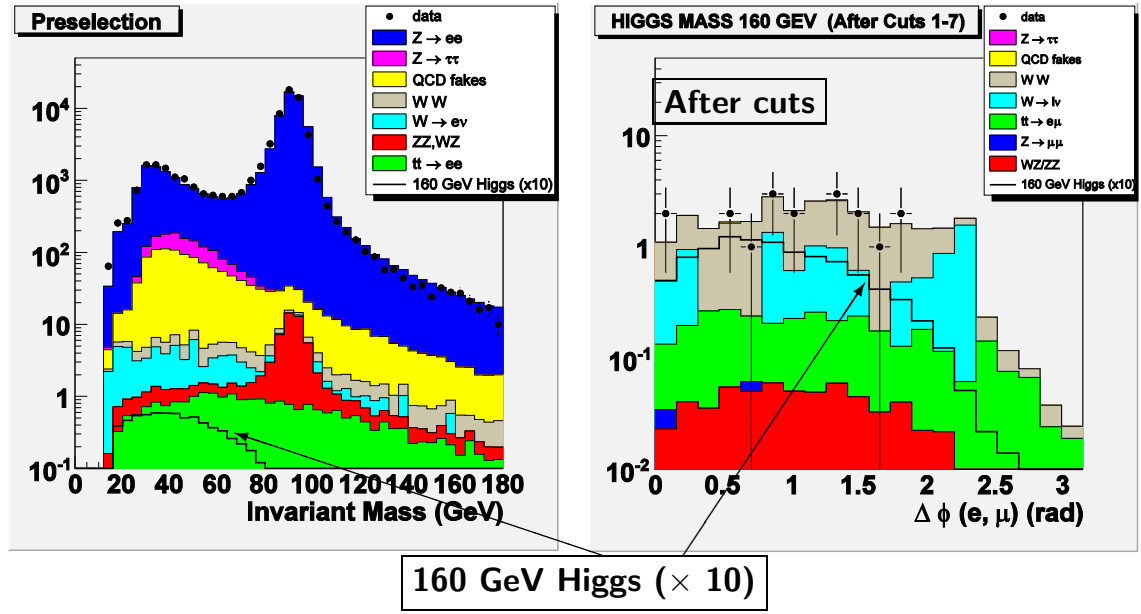
- Event selection includes:
  - Two leptons (e/μ) $p_T > 20/10$ GeV
  - $\not{E}_T > m_H/4$
  - Di-lepton invariant mass
    $m_{\ell\ell} > 16$ GeV
    $m_{\ell\ell} < m_H/2 - 5$ GeV
  - $\Delta\Phi(\ell\ell)$ distribution fitted to obtain 95% CL limit
- SM cross section still far away, but 4th generation models getting closer

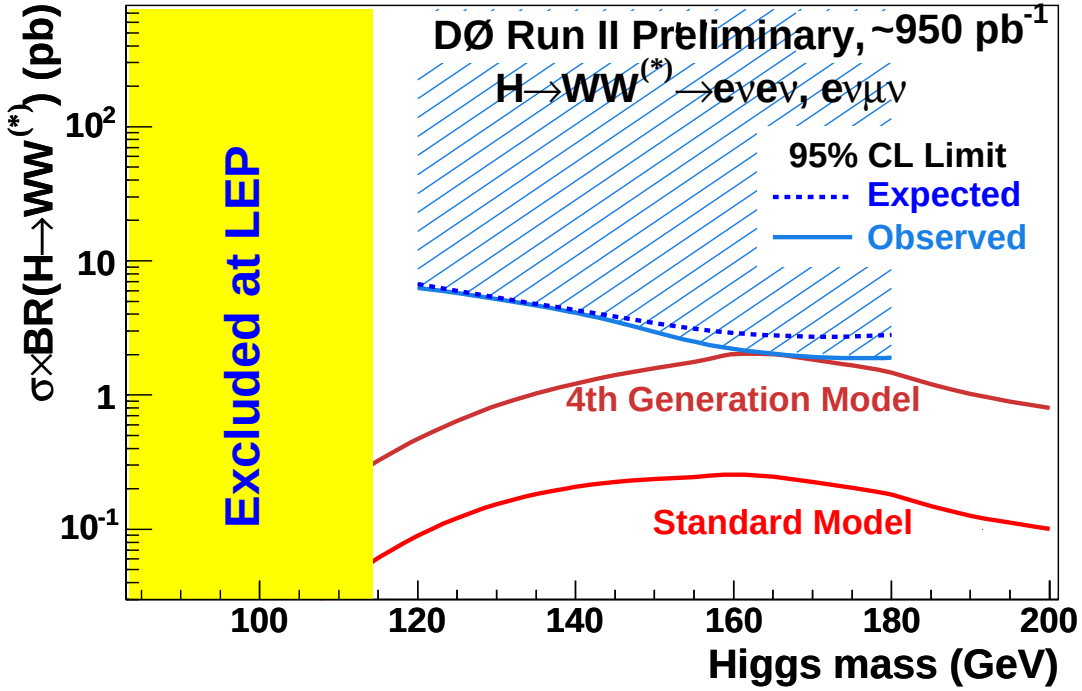




$H \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}, \ell = e, \mu$

- $\mathcal{L} = 950$ pb^{-1}
- ee and $e\mu$ channels
- Event selection includes:
  - Isolated e/μ
  - $p_T(\ell_1) > 20$ GeV
  - $p_T(\ell_2) > 15$ GeV
- $\not{E}_T > 20$ GeV
- Veto on
  - Z resonance
  - Energetic jets
- $m_H = 120$ GeV:
  - 31 events observed
  - 32.7±2.3 (stat) predicted
  - Background systematic uncertainty 15%
  - $\sigma_{95} = 6.3$ pb



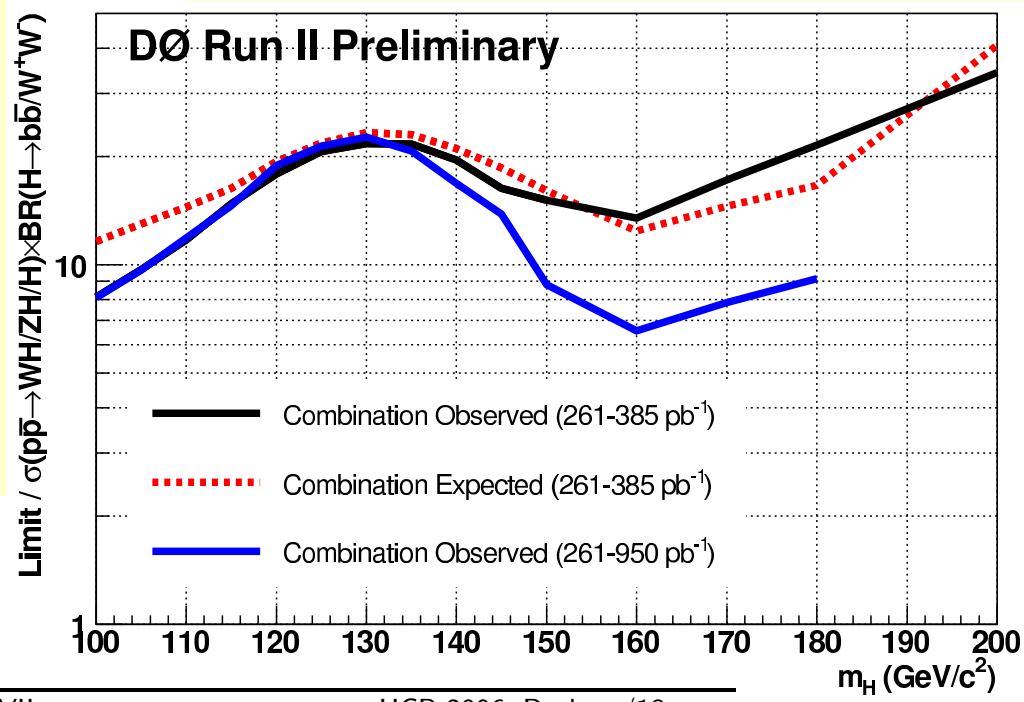


Combined SM Higgs Limits

Source	$WH \to e\nu b\bar{b}$	$WH \to \mu\nu b\bar{b}$	$WH \to \ell\nu b\bar{b}$	$ZH \to \nu\nu b\bar{b}$	$WH \to WW^+W^-$	$H \to W^+W^-$
Luminosity	X	X	X	X	X	X
Jet Energy Scale	X	X	X	X		X
Jet ID	X	X	X	X		
Electron ID	X				X	X
Muon ID		X			X	X
b-Jet Tagging	X	X	X	X		
Background σ	X	X	X	X	X	X

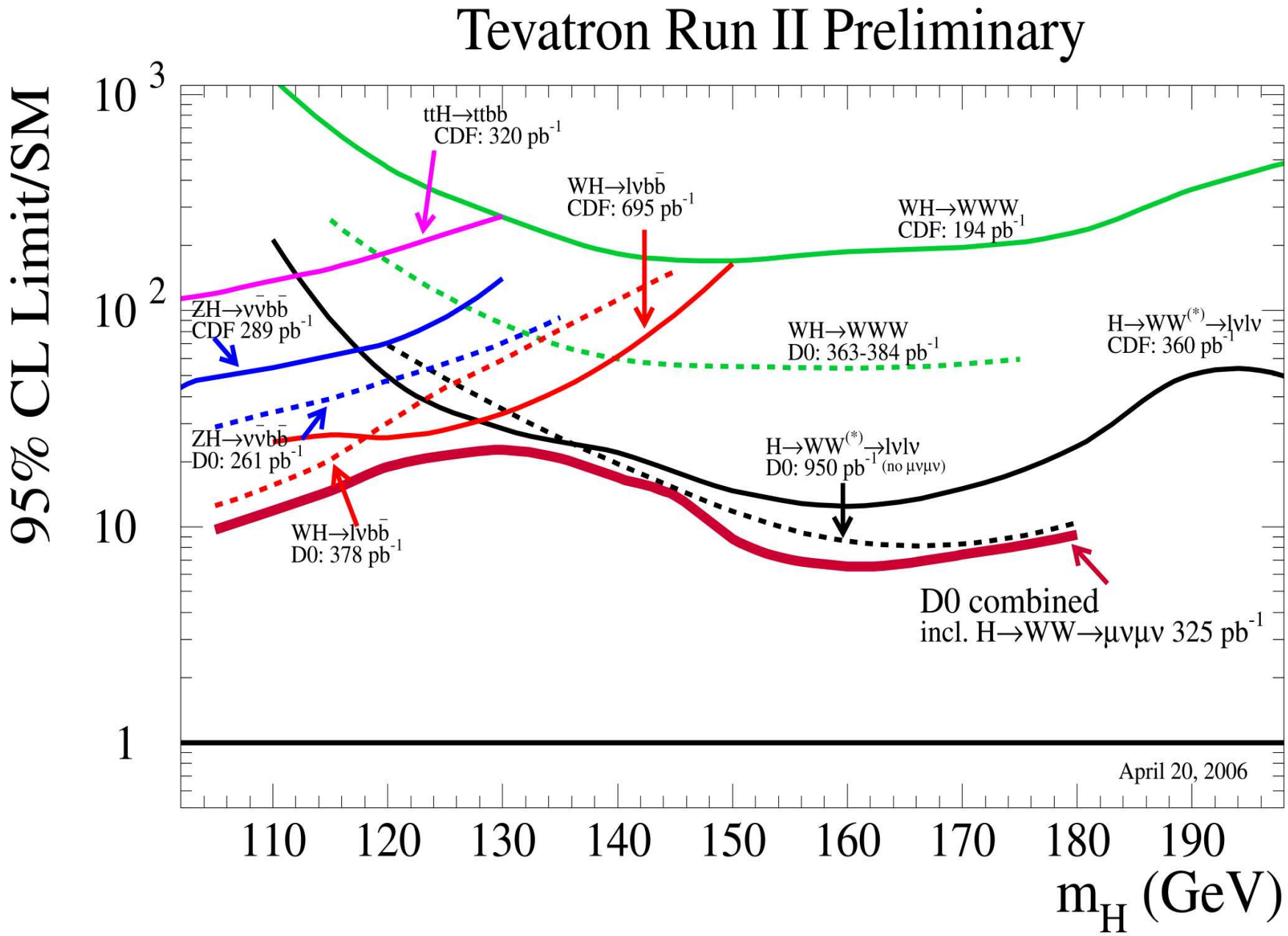
- New combined limit from all SM Higgs search channels!
- 14 orthogonal search channels (incl. single and double tag analysis and $WH \to \ell\nu b\bar{b}$ with missed lepton)
- Full account taken of systematic uncertainties
- High mass region benefits from $H \to WW$ analyses

- CLs (LEP) method used for combination
  - CLs confidence interval is normalization of CL_{S+B}
  - CL_{S+B} = signal + background hypothesis, CL_B = background only hypothesis,
  - $CL_S = CL_{S+B}/CL_B$, CL_{S+B} & CL_B are defined using a "test statistic"
  - Test statistic used: Log-Likelihood Ratio LLR$= -2\ln Q$ generated via Poisson statistics $Q = (s+b)^d e^{-(s+b)}/e^{-b}b^d$, s=sig., b=bak., d=data



Tevatron Higgs combination effort started

SM Higgs Limits



Sensitivity Prospects

$6\times$ more lumi, analyses improvements and combination with CDF will decrease cross section factor from 15 to 1

Ingredient	Equivalent Luminosity gain @ $m_H = 115$ GeV	Cross section factor $m_H = 115$ GeV	Cross section factor $m_H = 160$ GeV
Today with 330 fb^{-1}	—	15	12
$\mathcal{L} = 2.0$ fb^{-1}	6.00	6.1	4.9
NN b-tagger	2.50	3.9	
NN Analyses	3.0	2.2	2.8 (smaller gain)
Track Cal Jets	1.40	1.9	
Increased Acceptance	1.20	1.7	2.5
New channels	1.20	1.5	2.2
Reduced Systematics	1.20	1.4	
DØ CDF Combination	2.00	**1.0**	1.5
		OK with 2 fb^{-1}	$1.5^2 \times 2$ fb^{-1}=4.5 fb^{-1} needed

$\Rightarrow$ **95% CL exclusion for $m_H = 115 - 180$ GeV with 6 fb^{-1}**

Higgs Bosons in the MSSM

- Two complex Higgs doublets needed to avoid anomalies
- Eight degrees of freedom minus W^+, Z^0 longitudinal polarization states
  $\Rightarrow$ five scalars predicted: h, H, A, H^+, H^-
- CP-conserving models: h, H are CP-even, A is CP-odd
- At treee-level, two independent parameters:
  - m_A
  - $\tan\beta =$ ratio of VEV's
- Five more parameters intervene through radiative corrections:
  - M_{SUSY} (parameterizes squark, gaugino masses)
  - X_t (related to trilinear coupling $A_t \rightarrow$ stop mixing)
  - M_2 (gaugino mass term)
  - μ (Higgs mass parameter)
  - m_{gluino} (comes via loops)

Could have light Higgs but with small couplings

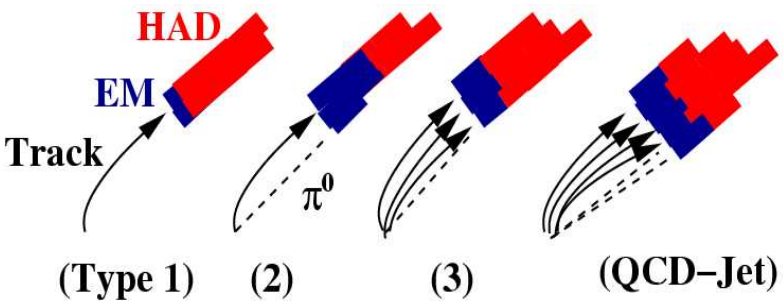
Parameter	m_h−max	no-mixing
M_{SUSY}	1 TeV	2 TeV
X_t	2 TeV	0
M_2	200 GeV	200 GeV
μ	$\pm$200 GeV	$\pm$200 GeV
m_g	800 GeV	1600 GeV

- $\Rightarrow$ Study 2×2 scenarios (cf. M Carena *et al.*, hep-ph/051123)

Neutral MSSM Higgs $\rightarrow \tau\tau$

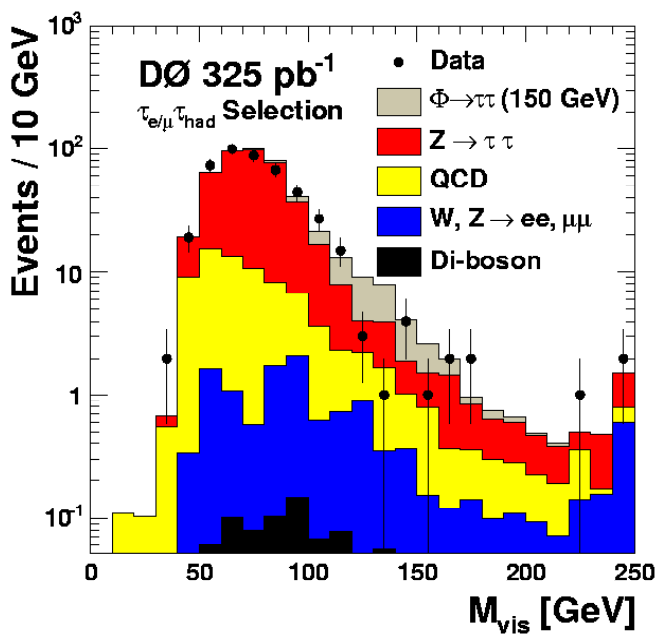
- Limits derived from $M_{vis} = \sqrt{P_{\text{vis}}(\tau_1) + P_{\text{vis}}(\tau_2) + \not{E}_T}$ likelihood fit
- Standard Model Backgrounds:
  - $Z \rightarrow \tau\tau$ (irreducible background)
  - $Z/\gamma^* \rightarrow ee/\mu\mu$, multi-jet, $W \rightarrow \ell\nu$, Di-bosons

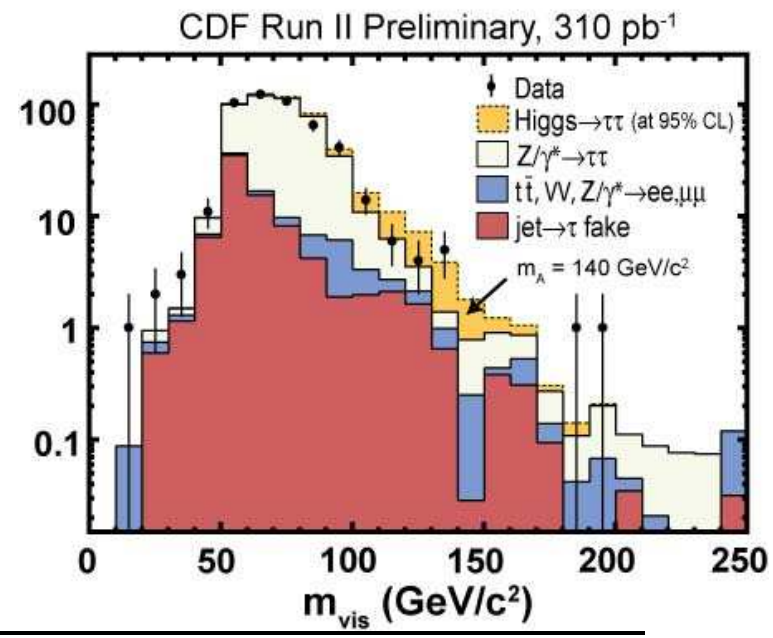
Different τ hadron decay topologies identification via NN (DØ)



	Channel	Data	Expected Background
DØ	$e + \tau_{\text{had}}$	484	427.3±55.3 (stat⊕sys⊕lum)
	$\mu + \tau_{\text{had}}$	575	576.3±61.5 (stat⊕sys⊕lum)
	$e + \mu$	42	43.5±5.3 (stat⊕sys⊕lum)

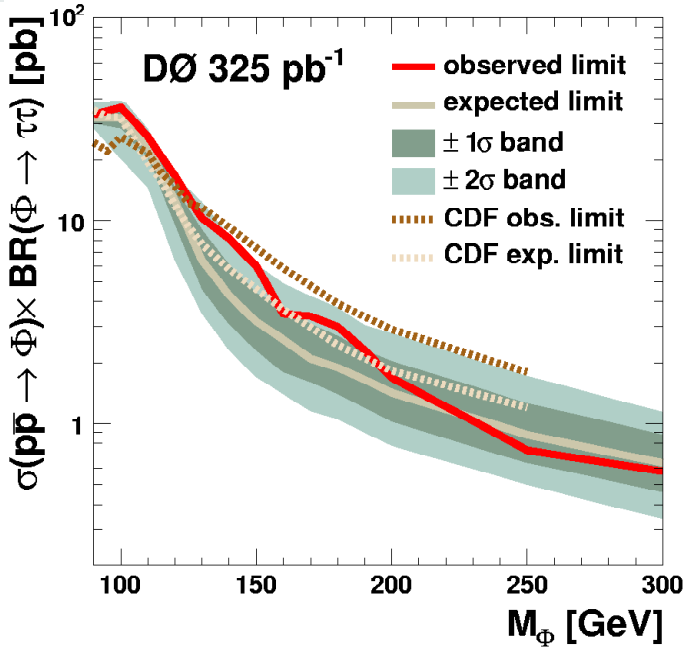
CDF Observed 487 events
Expected: 496±5.4 (stat)±27.7 (sys)±24.8 (lum)

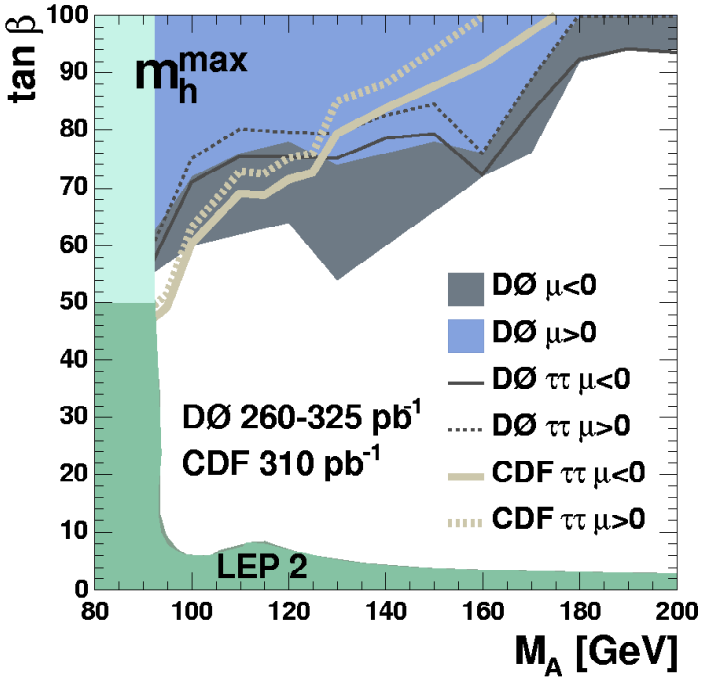


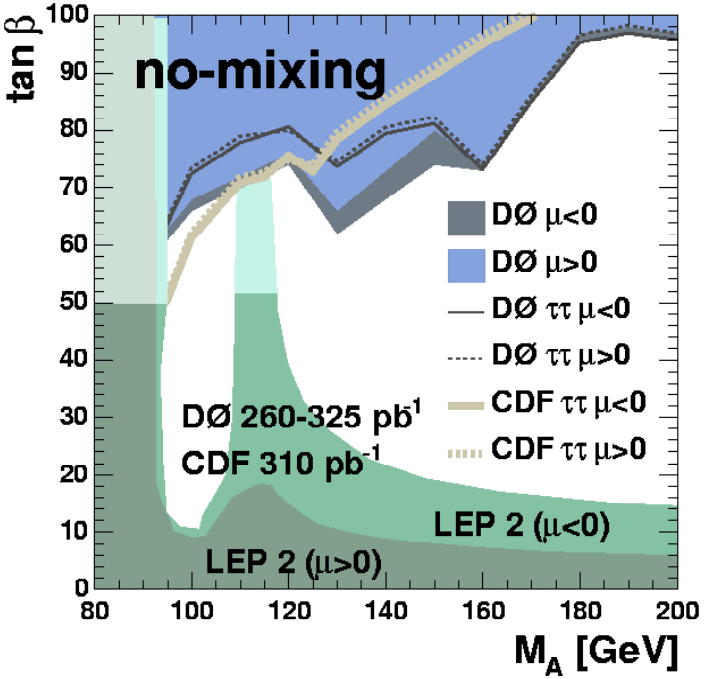


Neutral MSSM Higgs $\longrightarrow \tau\tau$

- Analysis including $e+\tau_{had}$, $\mu+\tau_{had}$, $e+\mu$ channels
- NN used for τ identification
- Invariant mass distribution fitted to derive limit
- Results combined with $hbb(b) \longrightarrow bbb(b)$ channel
- τ's become important!

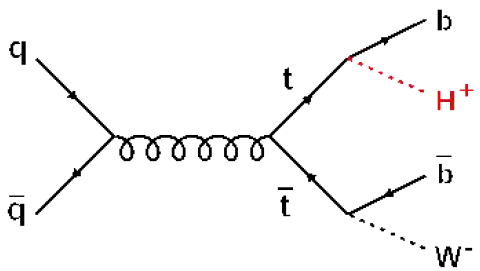






Charged MSSM Higgs

$t \to bH^+$ $(m_{H^+} < m_t - m_b)$



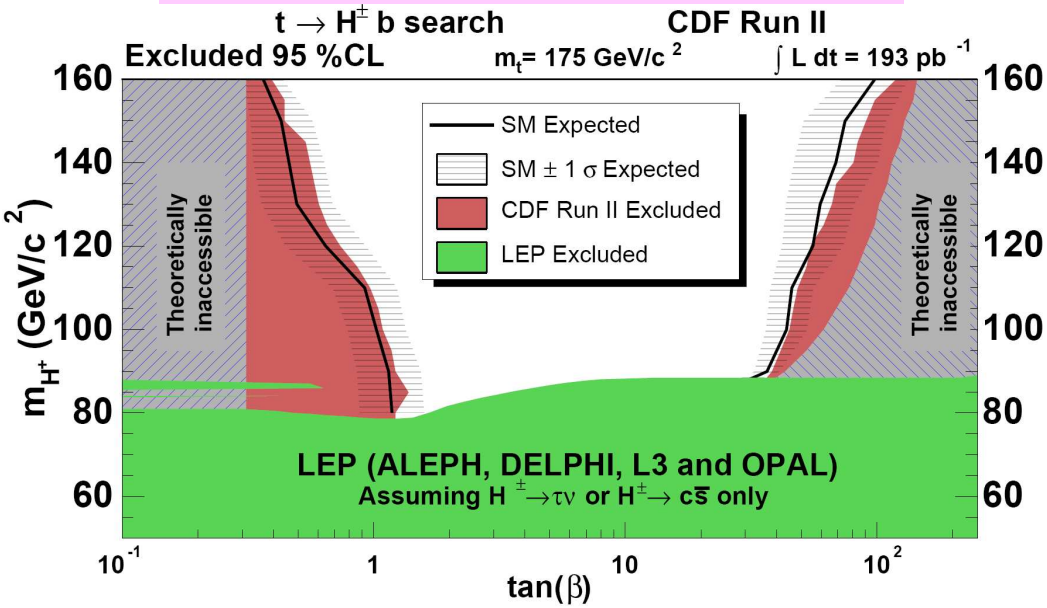
$\mathcal{L} = 193$ pb^{-1}

- Major decay modes: $H^+ \to \tau^+\nu$, cs, $t^*b \to W^+bb$, $W^+h \to W^+b\bar{b}$
- BR's depend on $\tan\beta$ and m_{H^+} (different from W^+ BR's)

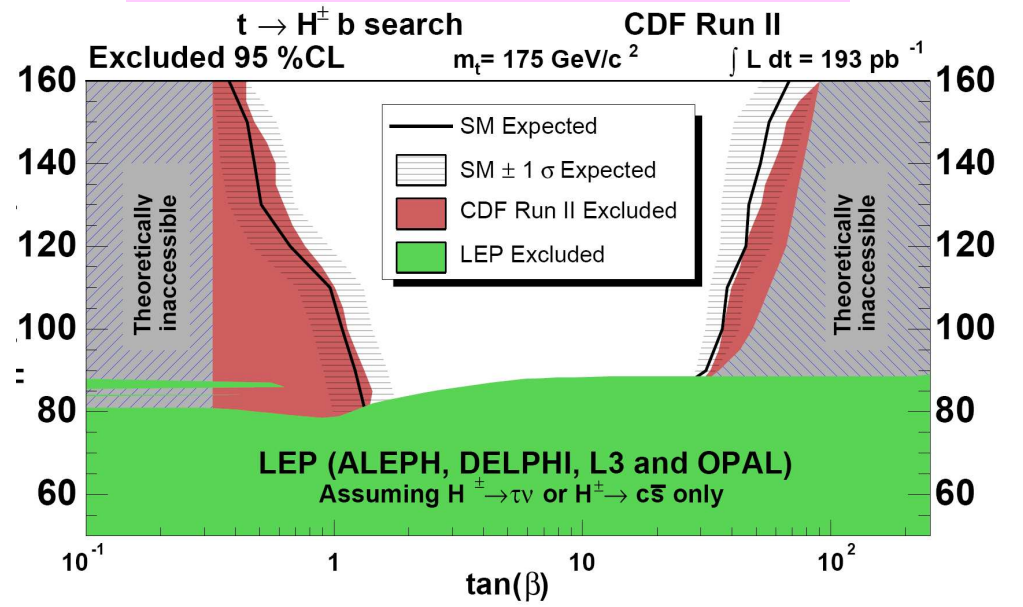
Final state	bg events	SM exp.	data
$2\ell+$ jets	2.7±0.7	11	13
$\ell+$ jets $(1b)$	20.3±2.5	54	49
$\ell+$ jets $(\geq 2b)$	0.94±0.1	10	8
$\ell + \tau+$ jets	1.3±0.2	2	2

$\Rightarrow$ Consistent with SM

No-mixing benchmark scenario



m_h−max benchmark scenario



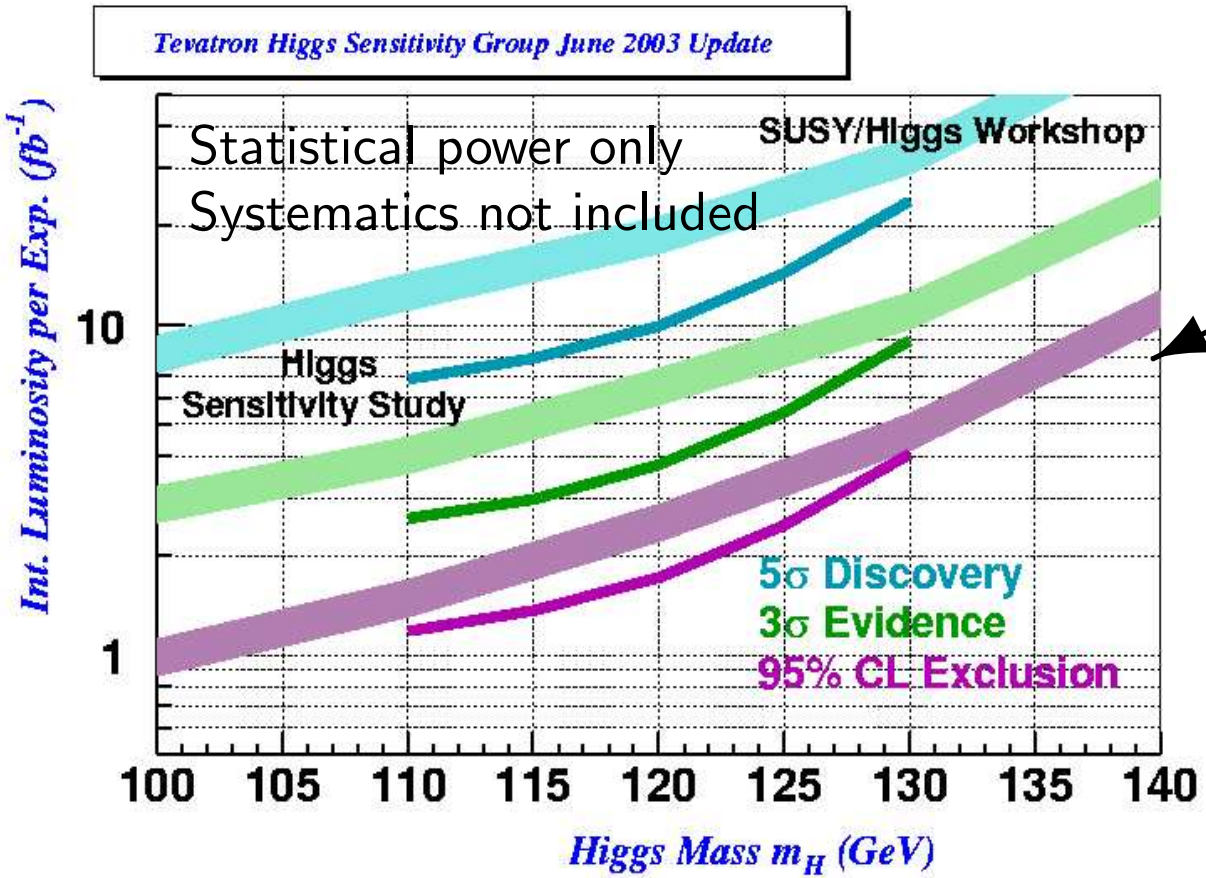
Summary

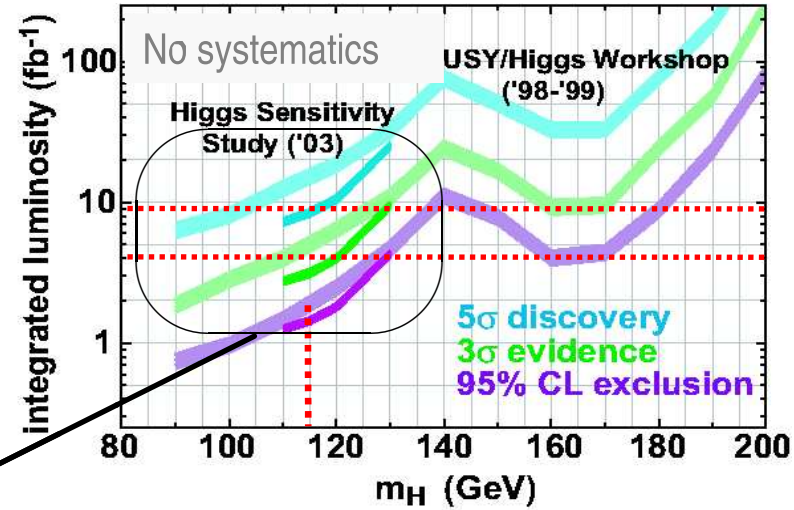
- Tevatron and Experiments are performing well
- A wide range of Higgs Searches has been performed by both CDF and DØ with up to 1 fb^{-1} Run II data:
  - No deviation from SM background expectation observed
  - No signal observed in MSSM Higgs search
- Work under way to improve Sensitivity
  - First combination of all SM channels from DØ
  - DØ-CDF combination efforts started
- Very exciting SM Higgs prospects for the future:
  - Sensitivity to $m_H > 114$ GeV starts with ~ 2 fb^{-1}
  - Exclusion up to 180 GeV possible with 6 fb^{-1}

Backup Slides

SM Higgs Sensitivity

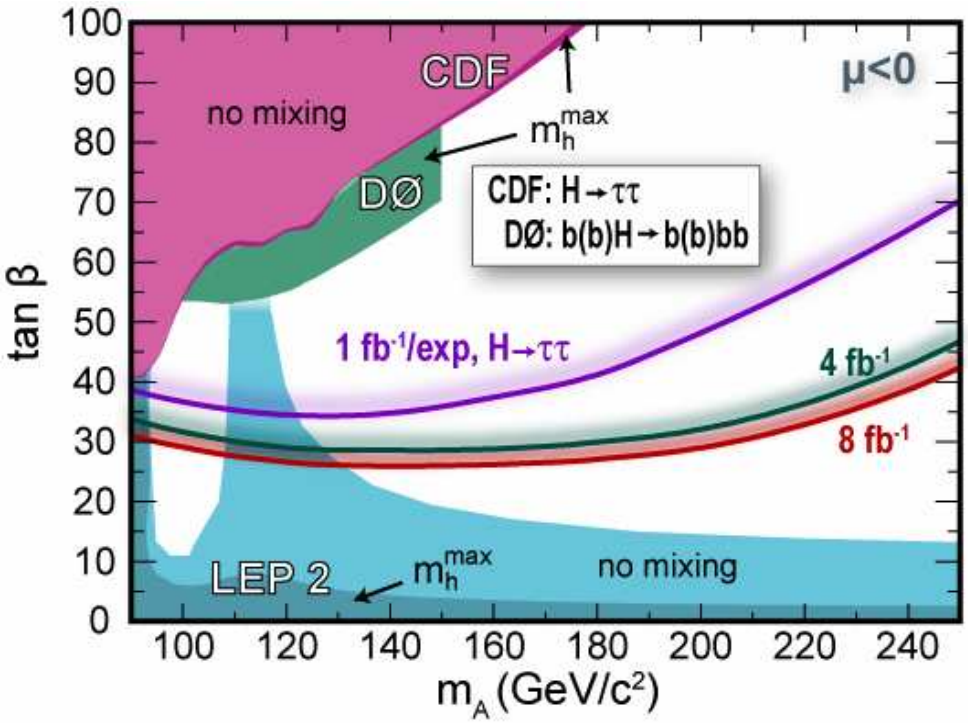
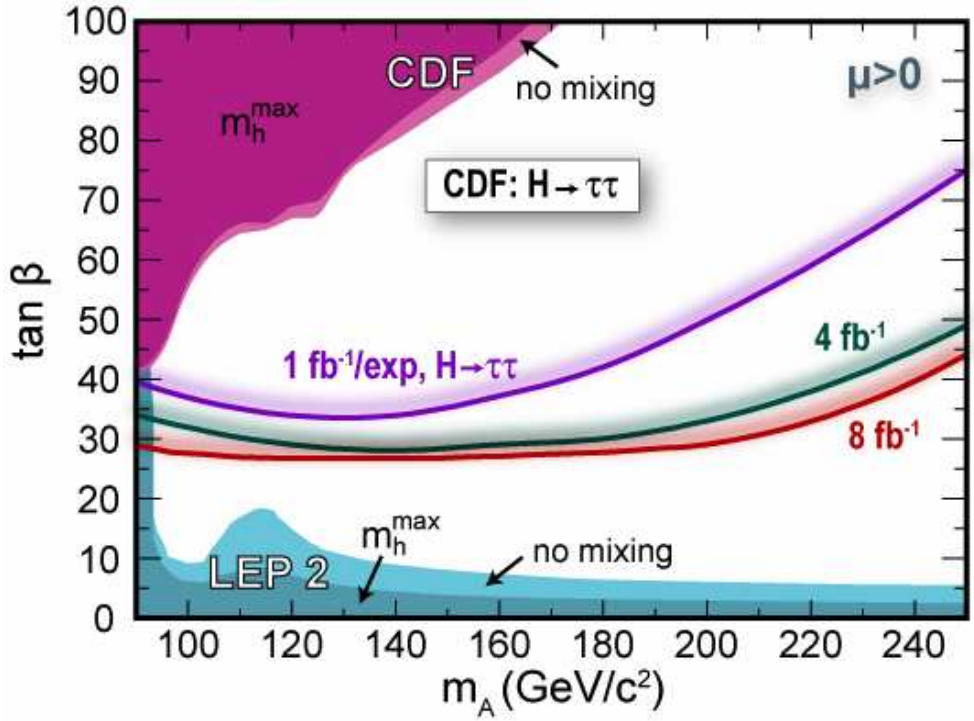
New Higgs sensitivity study from CDF + DØ in 2003:





Improved sensitivity from refined analysis and detailed simulation

The SM Higgs is a challenge, understanding of backgrounds is crucial

MSSM Higgs

- $m_h^{\max}$ and no-mixing scenarios with $\mu < 0$ and $\mu > 0$
- $b\bar{b}$ and $\tau\bar{\tau}$ Higgs decay channels are complementary
- Projections are based on current analysis techniques
- Many improvements being implemented