Higgs searches at the Tevatron

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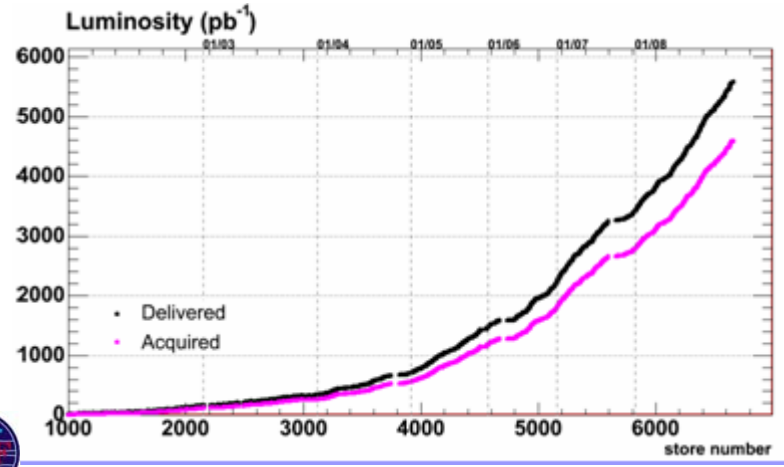
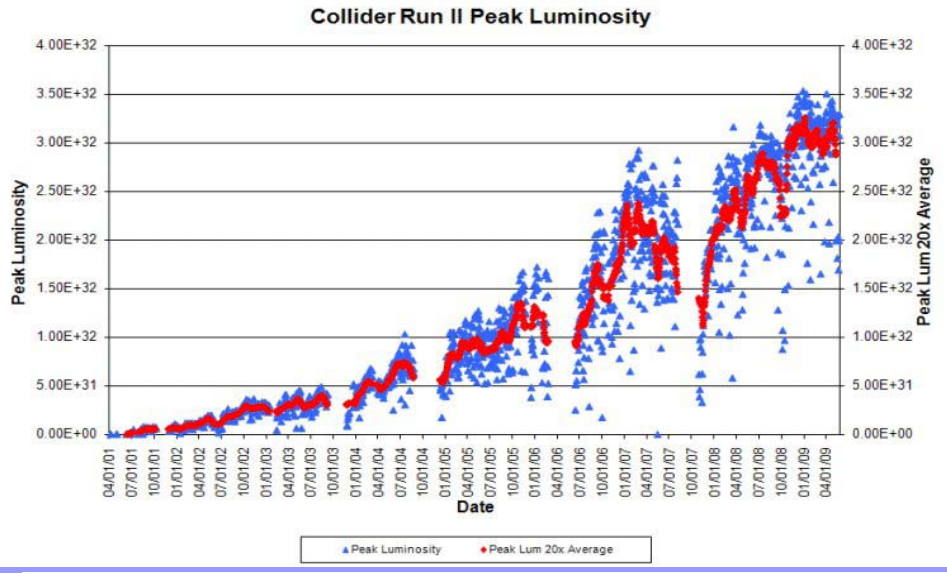
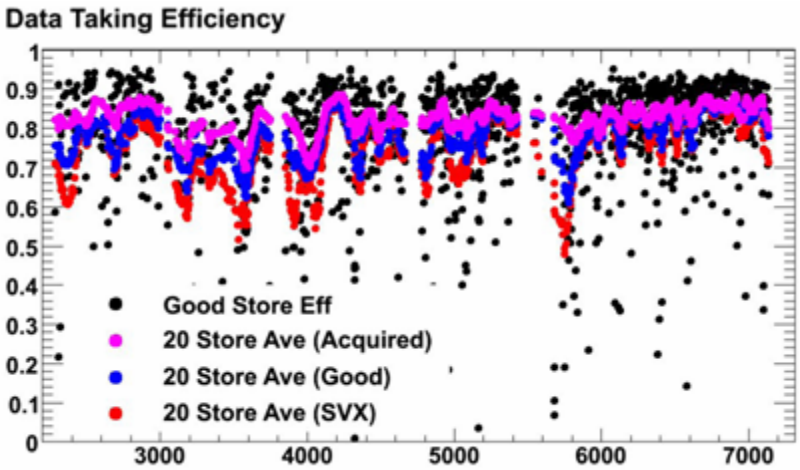
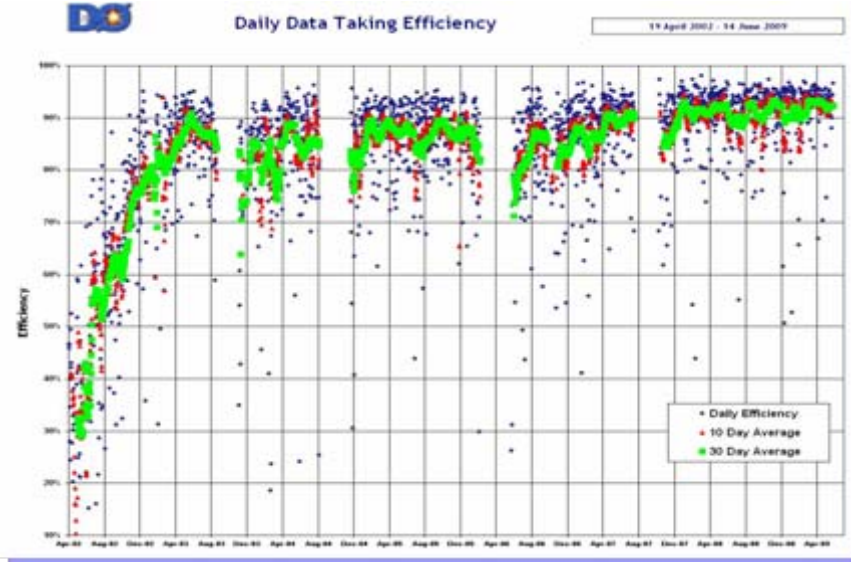
IFCA (Instituto de Física de Cantabria, CSIC-UC), on behalf of the CDF & D0 Collaborations

The Tevatron







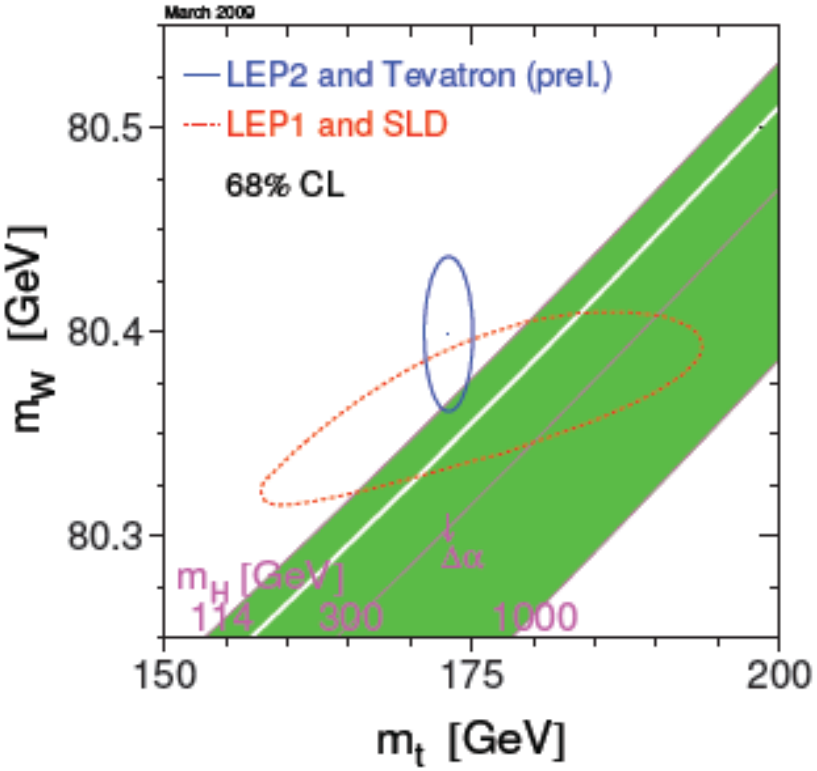


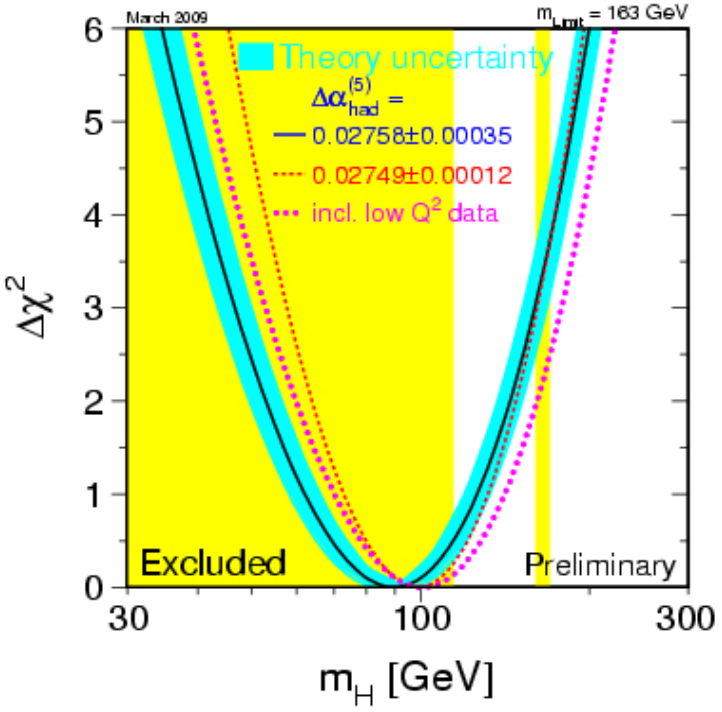
Standard Model

Standard Model

- **M_{top} and M_W global fits :** $m_{top} = 173.1 \pm 1.3$ GeV and $m_W = 80.399 \pm 0.023$ GeV
- **Global EW fit for Higgs mass:** $m_H = 90^{+36}_{-27}$ GeV

  $m_H < 163$ GeV @ 95 % CL





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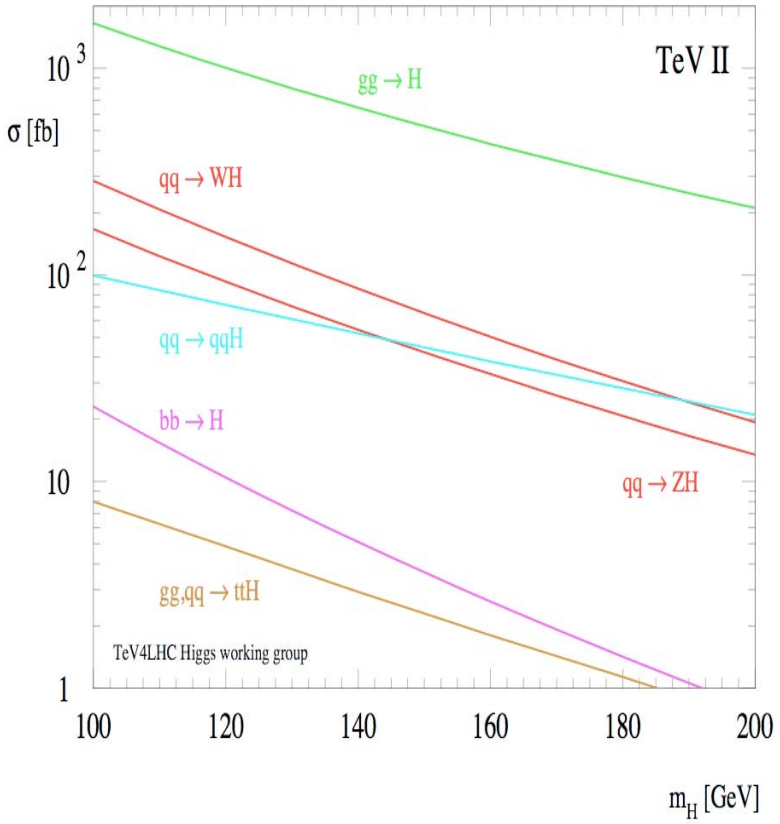
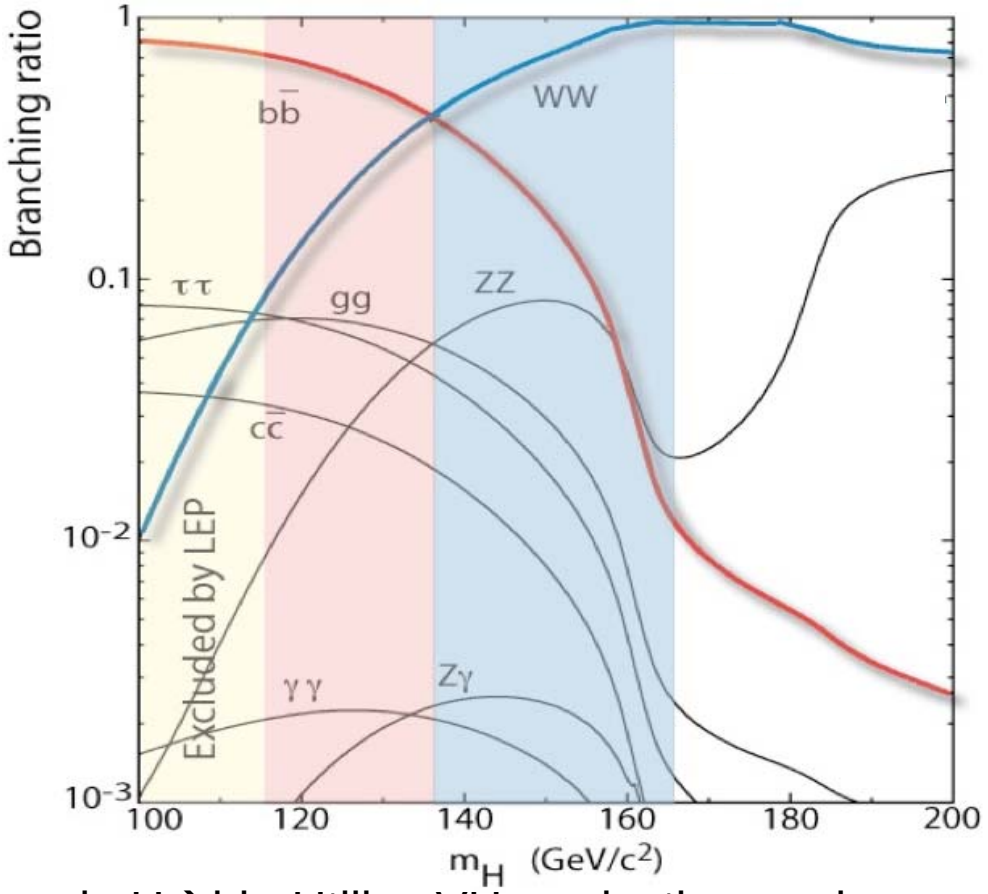
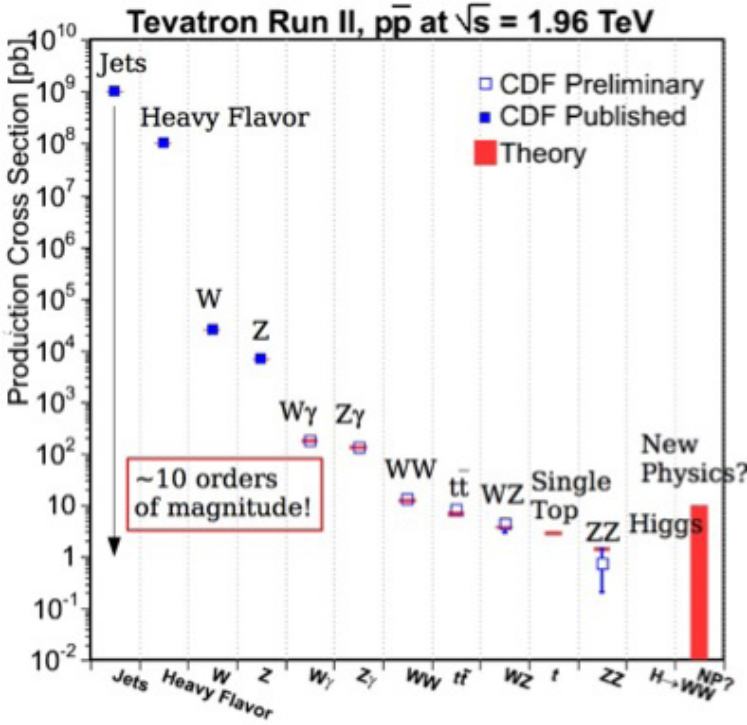


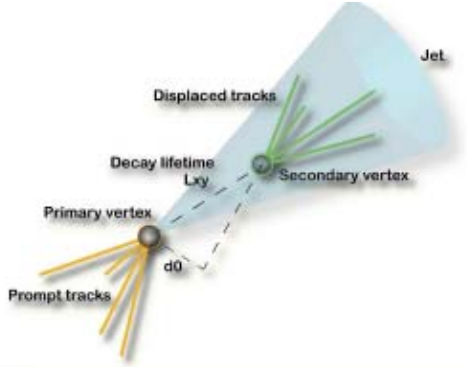


- M_H < 135 GeV, dominant decay mode H→bb. Utilize VH production modes (gg→H drowned by gg→bb)
- 135 GeV< M_H < 200 GeV , dominant decay mode H→WW, all production channels can be incorporated

Experimental Challenges

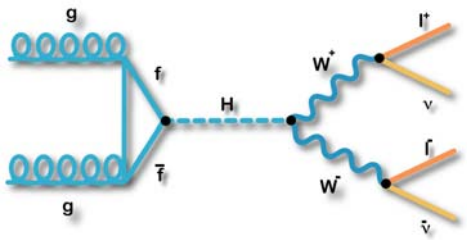
- The Challenge: extracts Higgs signal from backgrounds 10 orders of magnitude largers
- Trigger
  - High p_t leptons(e,μ) MET+Jets, τ dedicated
- Lepton ID: optimized on large W/Z samples
- b-jet tagging
  - D0: NN tagger based on b-lifetime information, with multiple operating points
  - CDF: Secondary Vertex and Jet Probability
- Background estimation is crucial
  - MC predictions: W/Z+jets, diboson, top,…
  - Data driven: mistags, QCD
  - Control regions
- Advanced analysis techniques to separate signal from background
  - Neural Network, Matrix Elements, Boosted Decision Trees…
  - Exhaustive checks in control regions

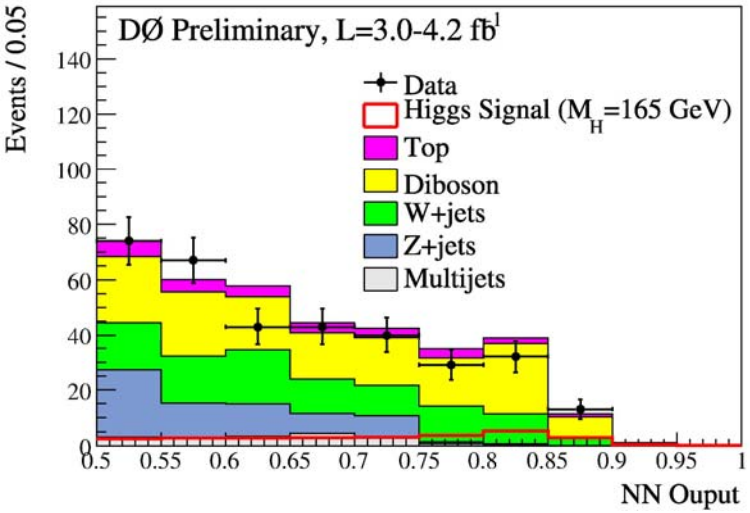


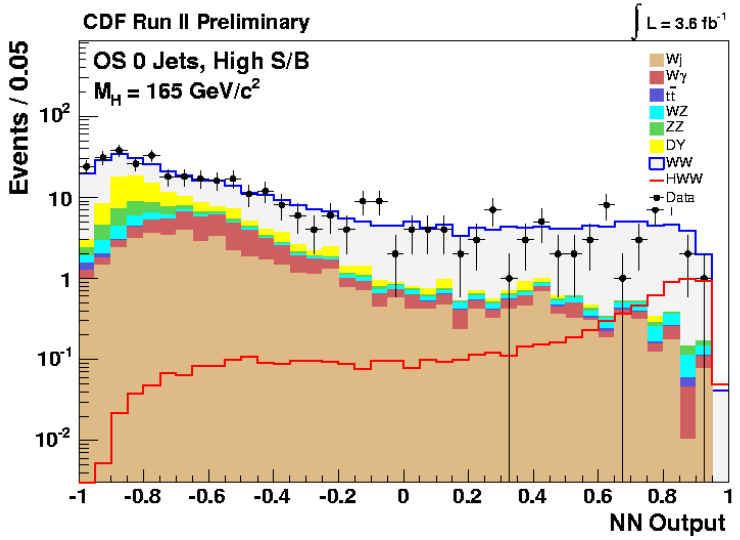


$H \to W^+W^- \to l^+ l^- \nu \bar{\nu}$

- **Most sensitive channel at the Tevatron for high mass**
- **Both CDF and D0:**
  - **2 high pt opposite-signed, isolated leptons**
  - **Missing transverse energy**
  - **Dilepton azimuthal separation**
- **Added sensitivity from ZH,WH and Vector Boson Fusion, including same sign dileptons**
- **D0:**
  - **Separate channels ee,μμ,eμ, NN optimized separately for each channel**
- **CDF:**
  - **Separate analysis for 0,1,2 jets**
  - **0 jets using NN with Matrix Element**
  - **1,2 jets, NN with kinematic inputs.**







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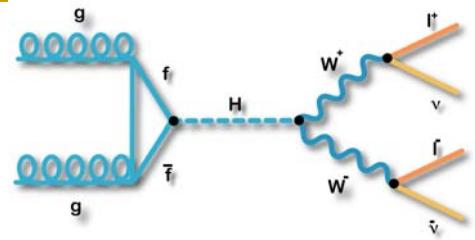
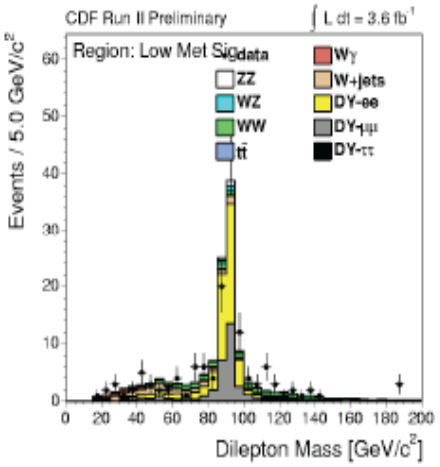
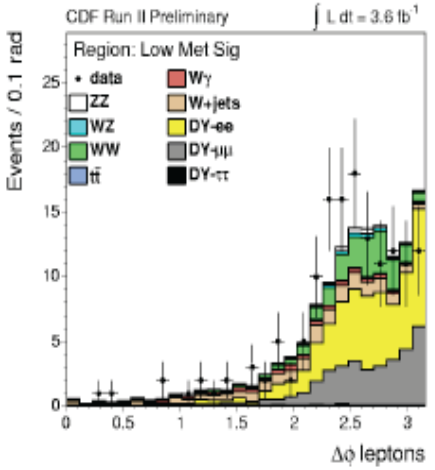
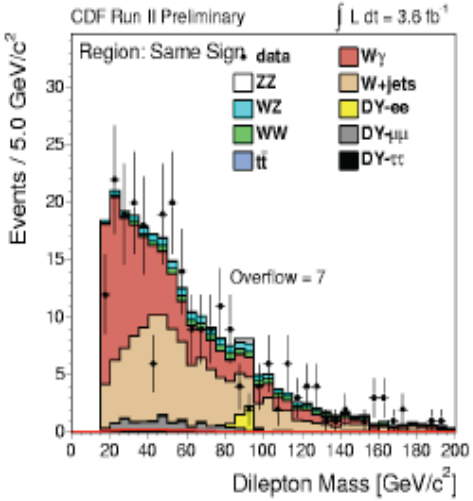
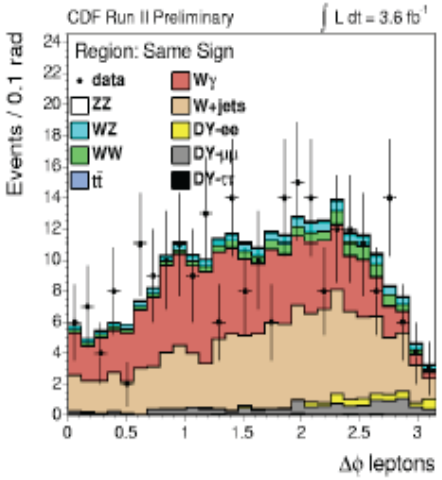


- Background:
  - WW, Drell-Yan, tt-bar, W plus jets,…
- Control regions:
  - Drell-Yan obtained by reversing missing Et requirements
  - Same-sign control sample to test modeling of jets and photons misidentified as leptons
  - t-tbar control sample consisting of two jet events with at least one b-tag









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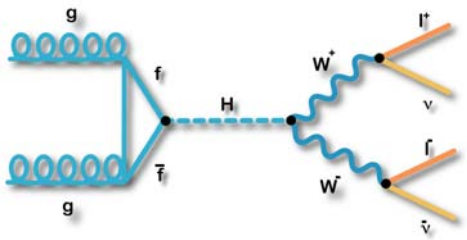
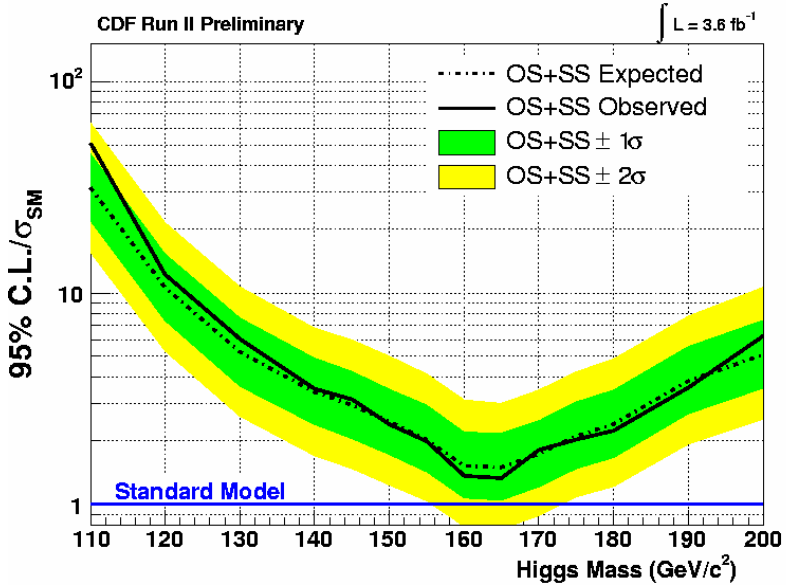
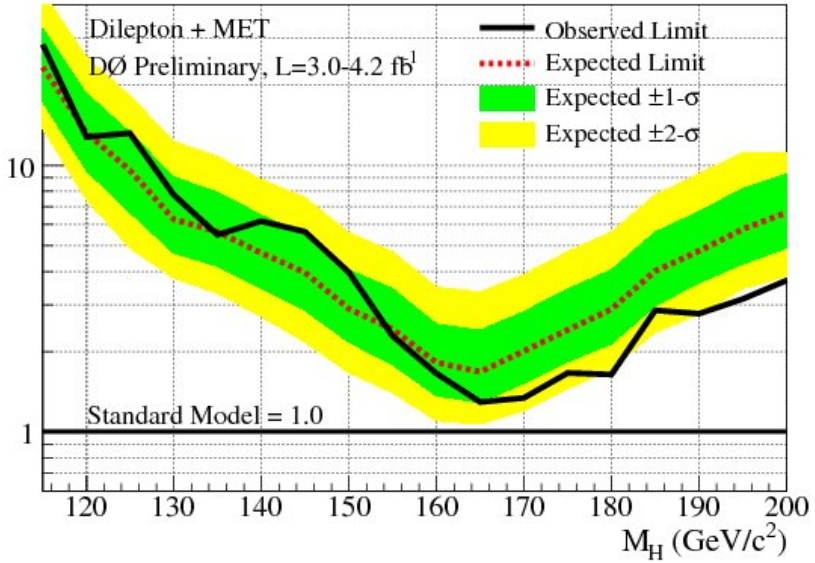


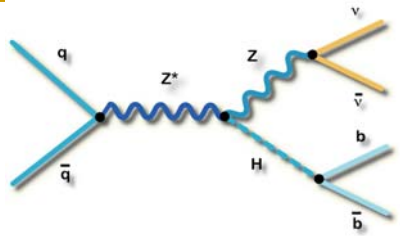
- Results:

Exp.	Lum.	Expected	Observed
	(fb^{-1})	95% CL	limit/SM
D0	3.0-4.2	1.8	1.7
CDF	3.6	1.5	1.4
M_H = 160 GeV			

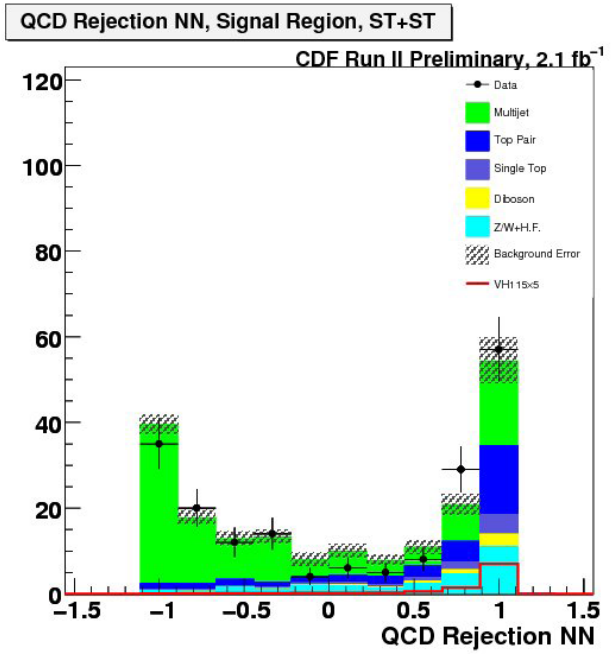


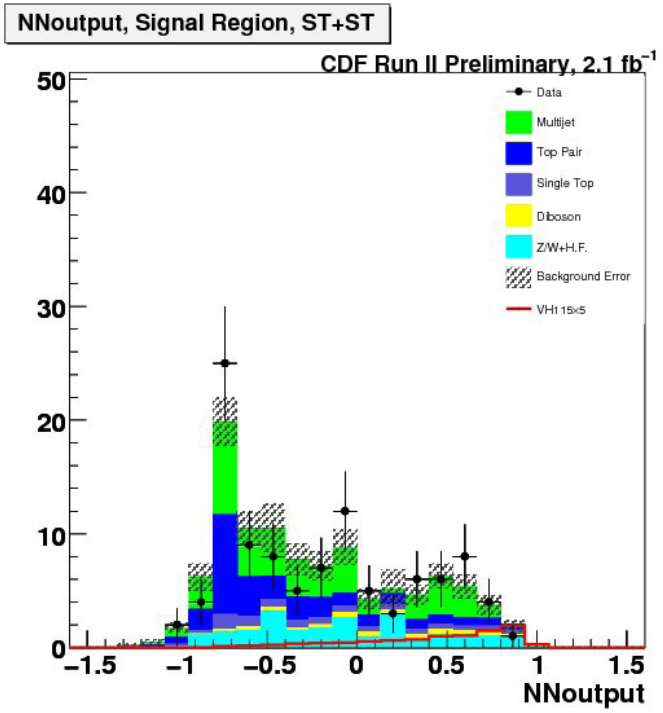


$ZH \rightarrow \nu\bar{\nu}b\bar{b}$



- Missing Et plus b-jets.
- Incorporates acceptance from WH in cases where the lepton is not reconstructed
- Both, CDF and D0:
  - Veto events with a lepton
  - Control regions to model QCD background and W+jets background
- CDF:
  - QCD background removed with a NN
  - Three non-overlapping samples by b-tagging categories
  - A second NN to separate signal from background
- D0:
  - Use two b-tagged jets, one tight, one loose
  - Separate signal from background using a BDT





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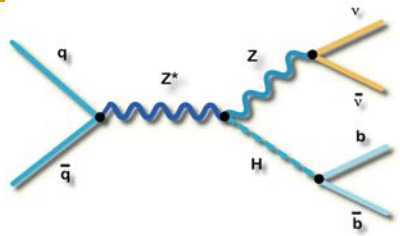

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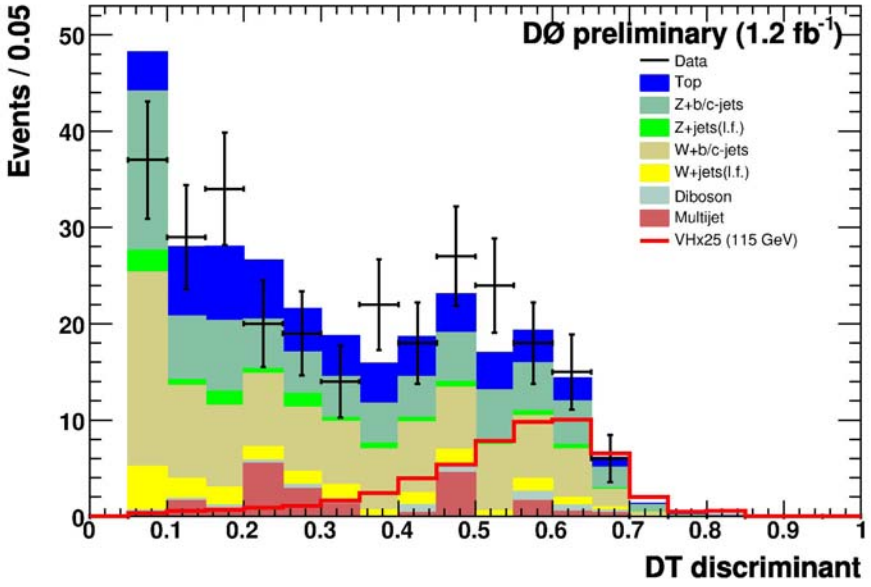
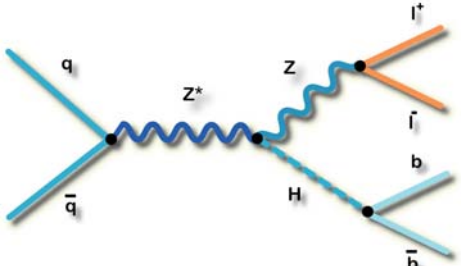
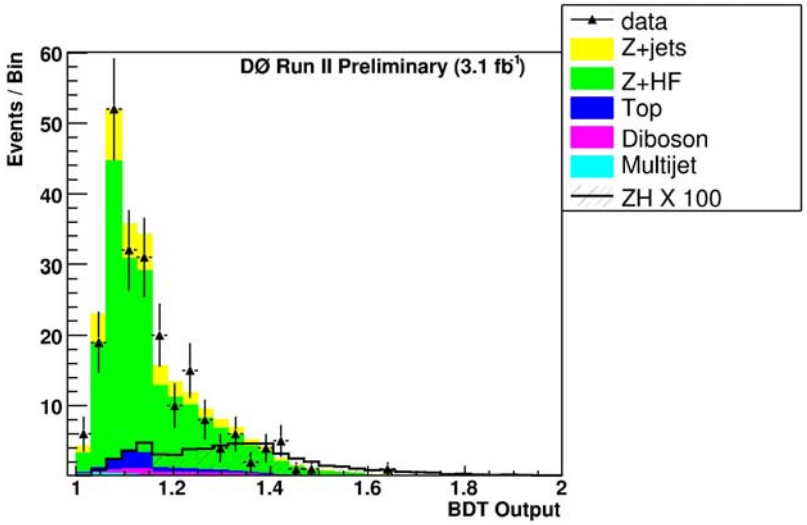


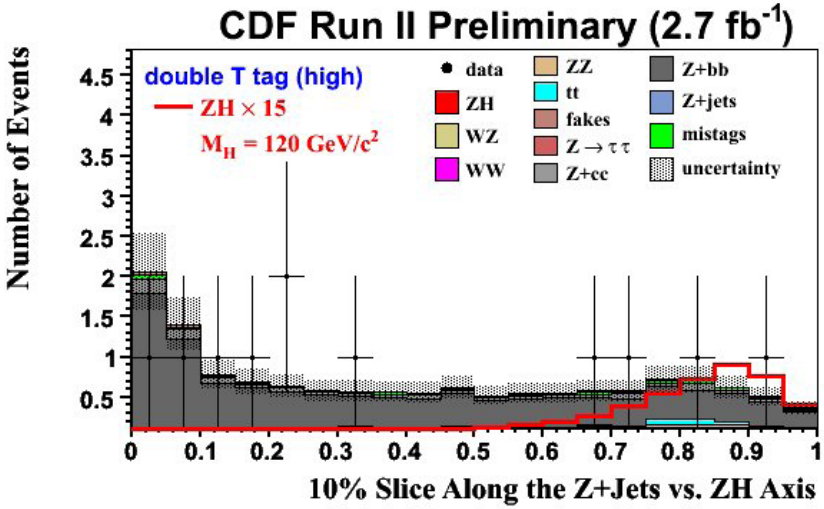
Exp.	Lum.	Expected	Observed
	(fb^{-1})	95% CL	limit/SM
D0	2.1	8.4	7.5
CDF	2.1	5.6	6.9
M_H = 115 GeV			

$ZH \to \ell^+ \ell^- b\bar{b}$



- It has the cleanest signature, (low multijet and W+jets background) but small BR
- Two isolated high pt leptons, two or more jets (at least one b-tag)
- Backgrounds mainly Z+jets, QCD
- Both CDF and D0:
  - Use Σp_t constraint to sharpen Mjj resolution
  - Split sample in b-tagging categories
- CDF :
  - Improve mass resolution assigning missing Et with a NN
  - 2-dimensional NN or ME
- D0 :
  - NN and BDT





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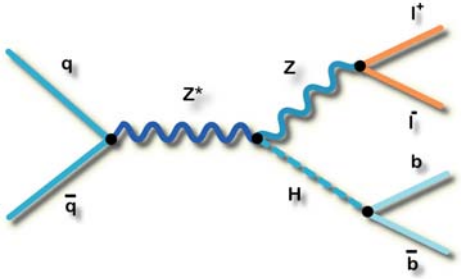

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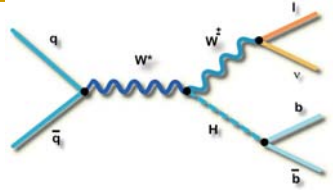
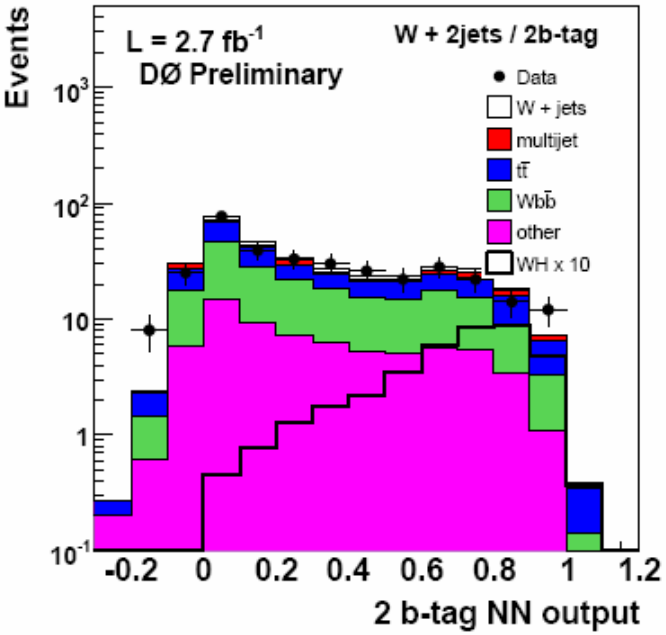
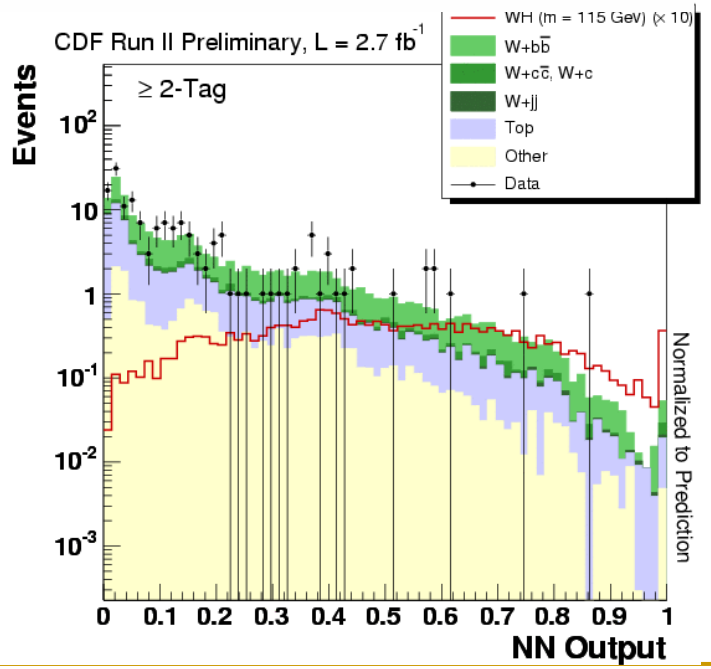
Exp.	Lum.	Expected	Observed
	(fb^{-1})	95% CL	limit/SM
D0	4.2	8.0	9.1
CDF NN	2.7	9.9	7.1
CDF ME	2.7	12.21	7.8
M_H = 115 GeV			

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



- It is the most sensitive channel at low mass
- Both CDF and D0:
  - High Pt lepton, missing Et, two jets (one or two b-tag), veto Z´s, cosmics and conversions (more than one isolated lepton)
  - Events grouped by tagging categories
- CDF :
  - Included isolated track not identified as lepton, split also in categories
  - Two analysis (NN, BDT, with ME included) and combination of both in a superdiscriminant
- D0
  - Uses NN (includes ME in 2 jet sample, Mjj in 3 jets)
  - WH→ τνbb-bar included





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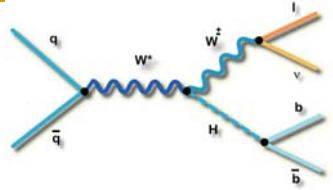

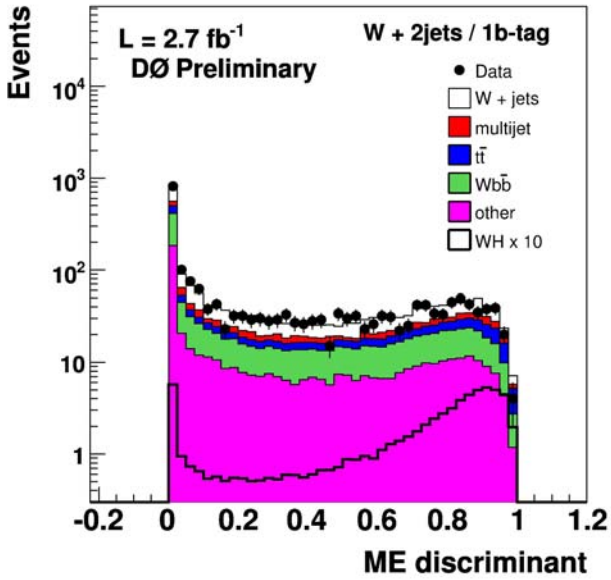

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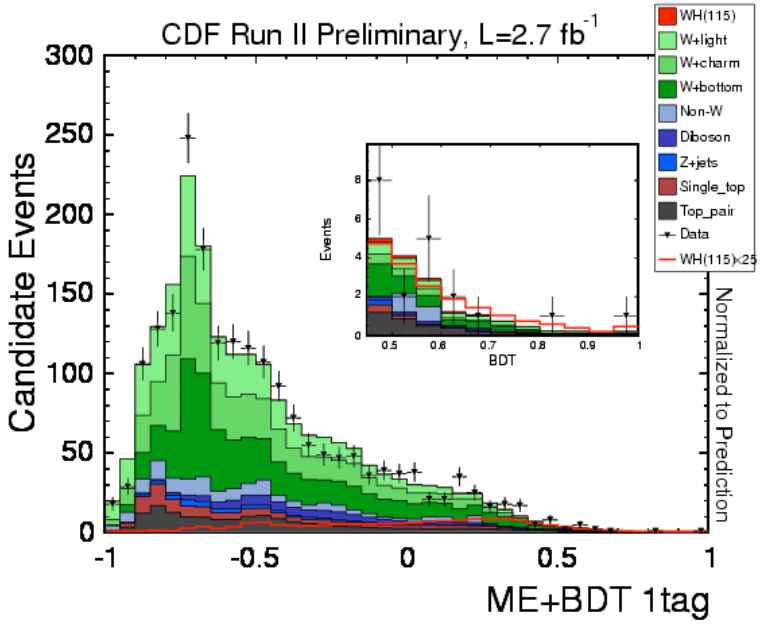

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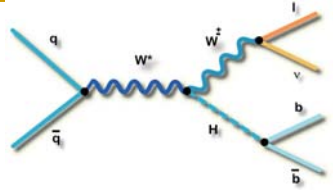
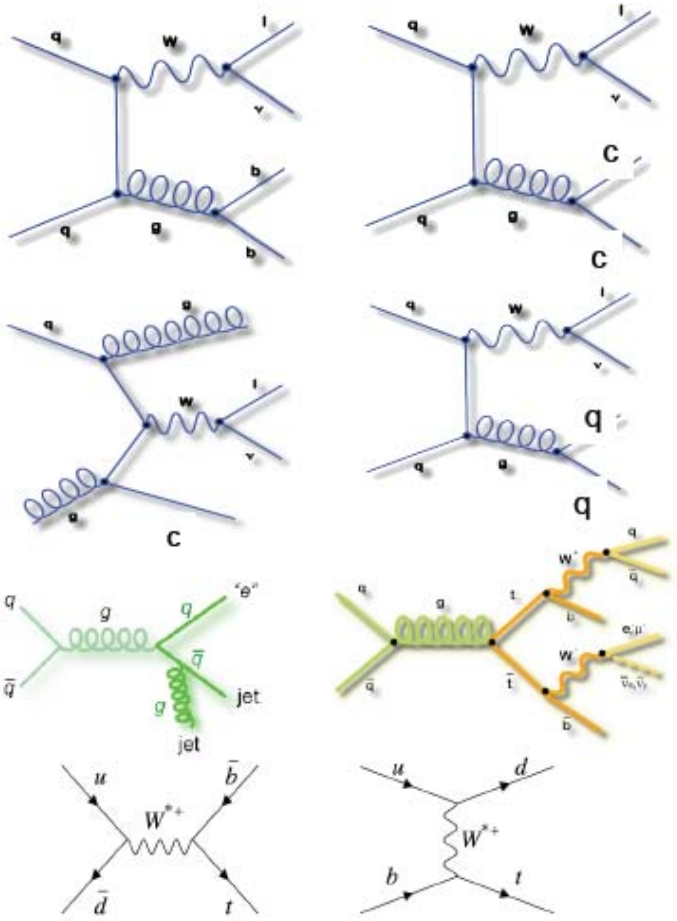


- Backgrounds from W,Z+jets, top, mistags, QCD,…

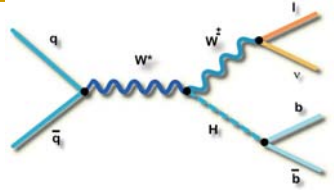


CDF, 2,7 fb^{-1}

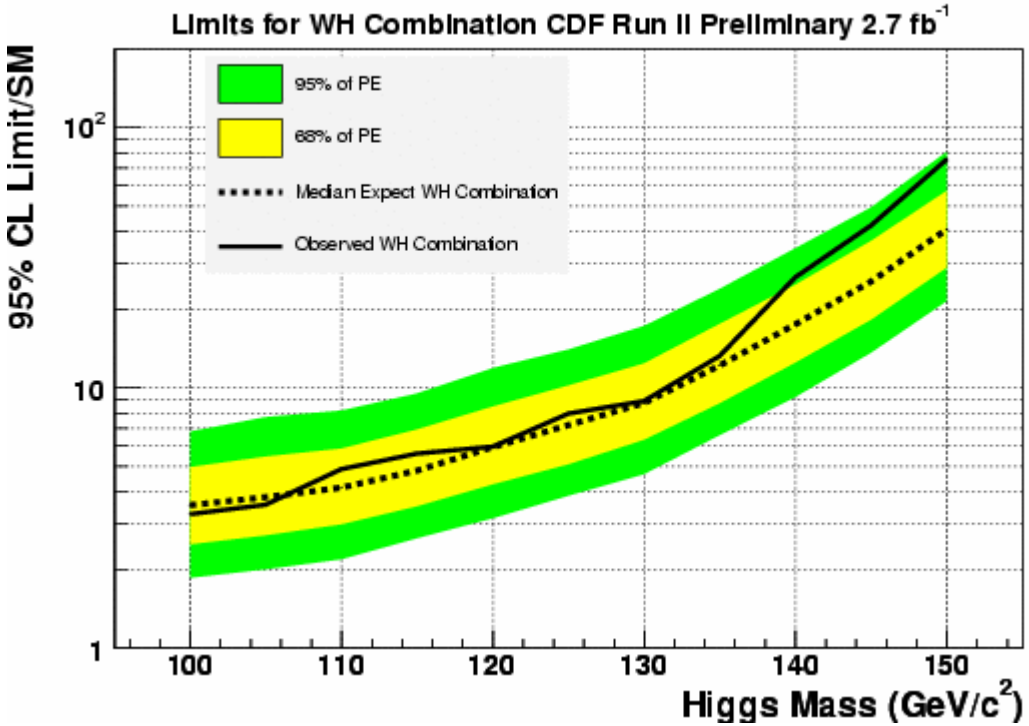
Process	1 Tag	2 Tags
WW	56.2 ± 6.2	0.4 ± 0.1
WZ	23.0 ± 1.7	4.8 ± 0.5
ZZ	0.8 ± 0.1	0.2 ± 0.0
TopLJ	121.3 ± 17.1	23.8 ± 3.9
TopDil	48.8 ± 6.8	14.1 ± 2.3
Stop T	64.0 ± 9.3	1.8 ± 0.3
Stop S	40.6 ± 5.7	12.8 ± 2.1
Z+jets	37.4 ± 5.5	2.1 ± 0.3
Wbb	538.7 ± 162.5	70.3 ± 22.5
Wcc/Wc	489.1 ± 150.9	6.8 ± 2.3
W+LF	458.0 ± 57.9	2.2 ± 0.6
QCD	135.5 ± 54.2	9.0 ± 3.6
Total Bg	2013.3 ± 324.1	148.2 ± 26.1
WH115	6.3 ± 0.5	2.0 ± 0.2
Data	1998	156

Some Background processes are modeled using MC simulation and others from data using control regions

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



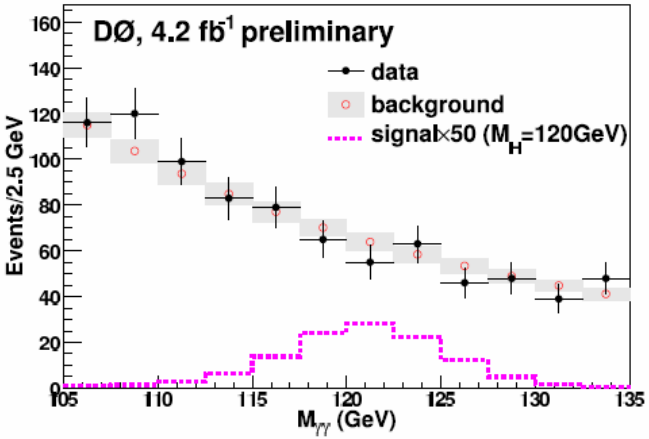
- Results



Exp.	Lum.	Expected	Observed
	(fb^{-1})	95% CL	limit/SM
D0	2.7	6.7	6.4
CDF	2.7	4.8	5.6
M_H = 115 GeV			

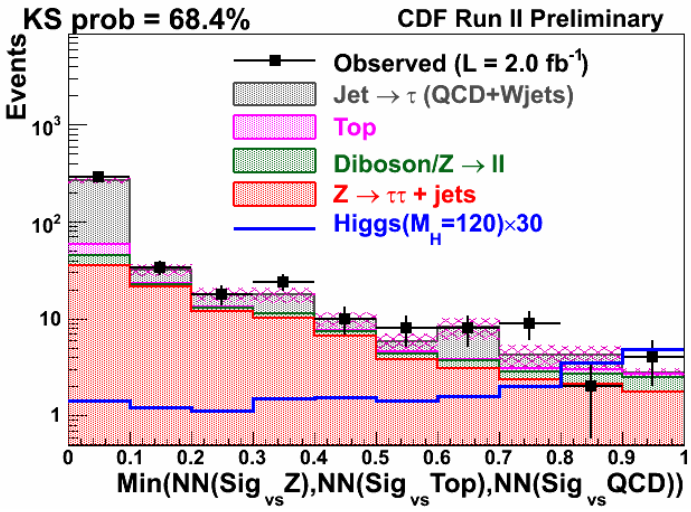
OTHER CHANNELS (low sensitivity)

Channel	CDF	D0
WH→WWW	3.6 fb^{-1}	2.7 (1.1*) fb^{-1}
ttH→ttbb	0.3 (-*)fb^{-1}	2.1 fb^{-1}
HX→ττ +jets	2 fb^{-1}	1.0 fb^{-1}
H→γγ	-	4.2 fb^{-1}



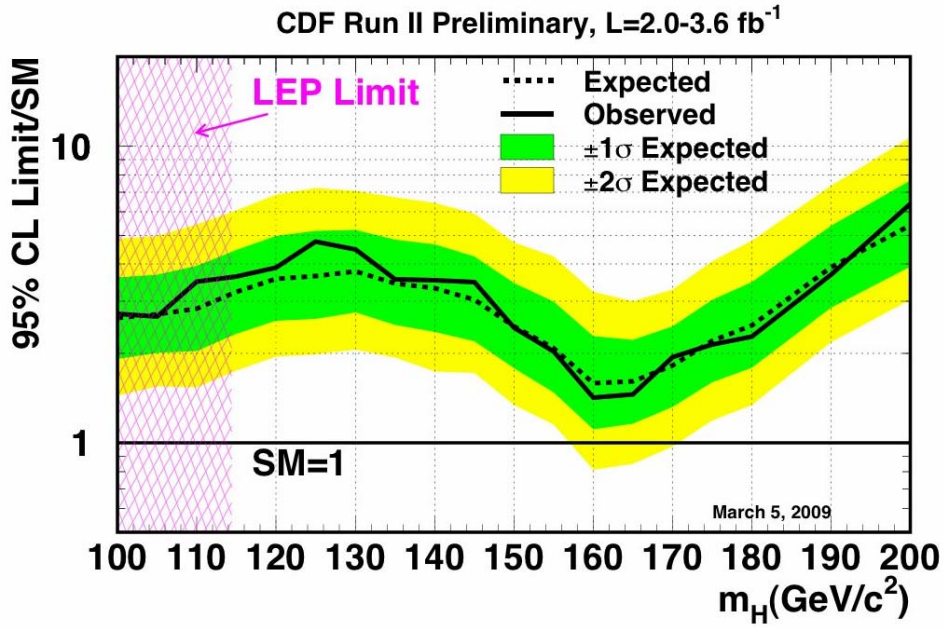
* (Lumin. used in the combination. In the rest of cases all the lum. shown was used)

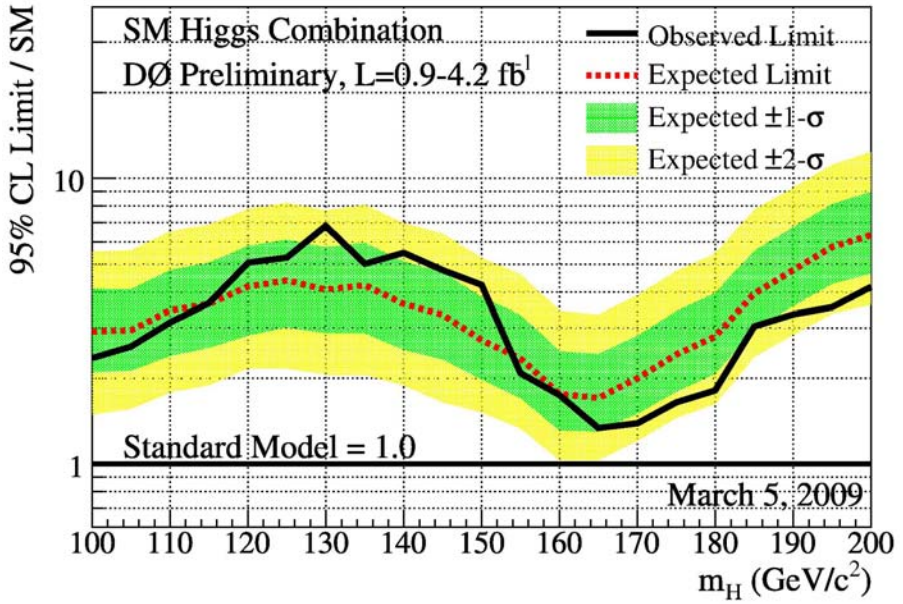
More ongoing analysis, not updated yet. Reaching SM sensitivities requires exploiting all possible decay channels



CDF and D0 Combinations

- Combining 75 different channels, all discriminant distributions analyzed
- Using Bayesian and Modified Frequentist methods to provide independent cross-check (better than 10% consistency required). Take weaker limits to be conservative.
- Systematics uncertainties
  - Rate systematics, affects normalization of discriminators
  - Shapes systematics, modify shape of discriminators, small effect on sensitivity
  - Correlations included

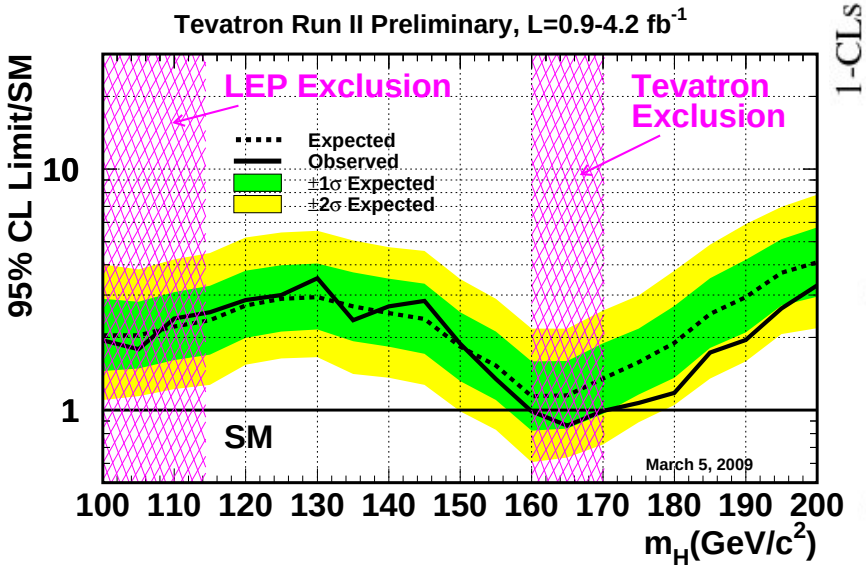


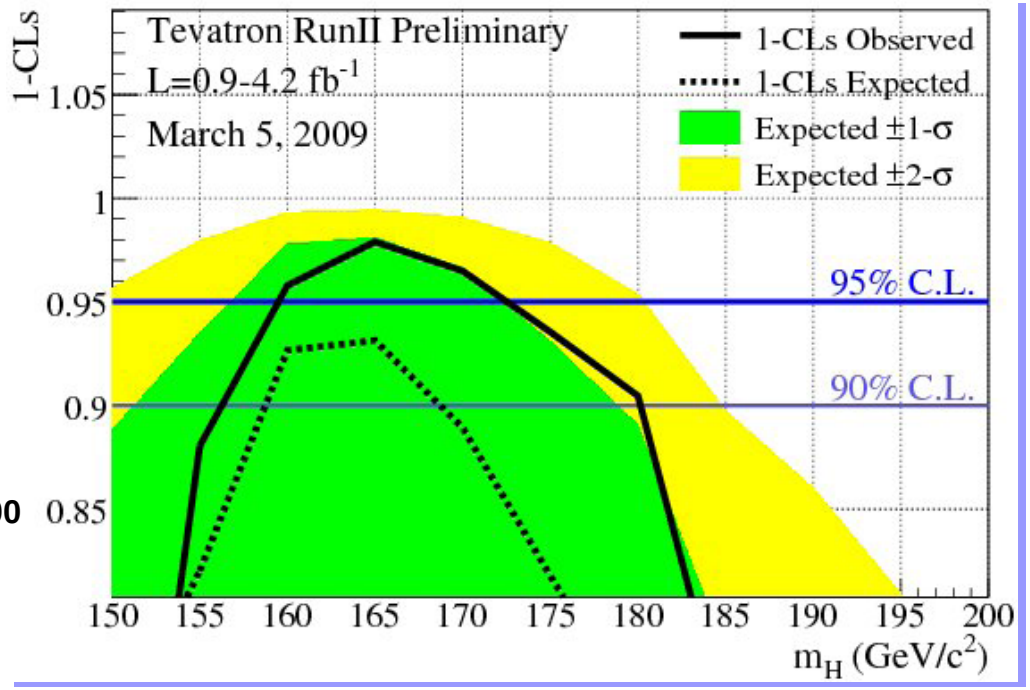


CDF and D0 Combinations

- Based on latest gg→H theoretical calculations (including two-loop electroweak effects), using MSTW 2008 NNLO PDF´s

Exclude a Higgs mass from 160 to 170 GeV at 95% CL

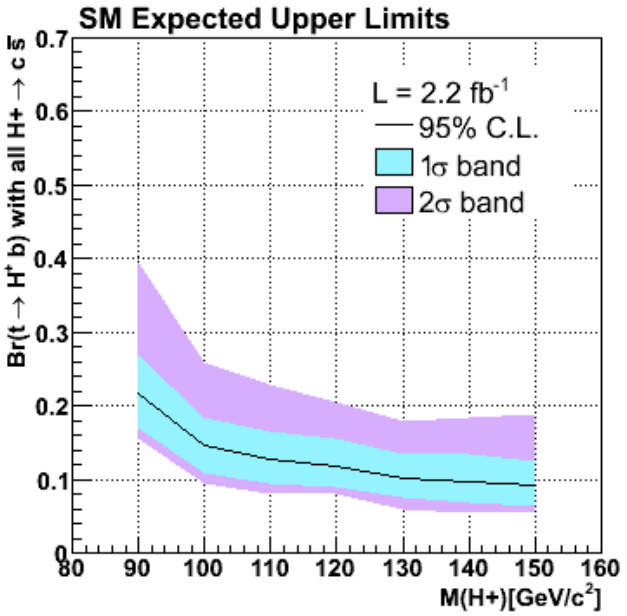




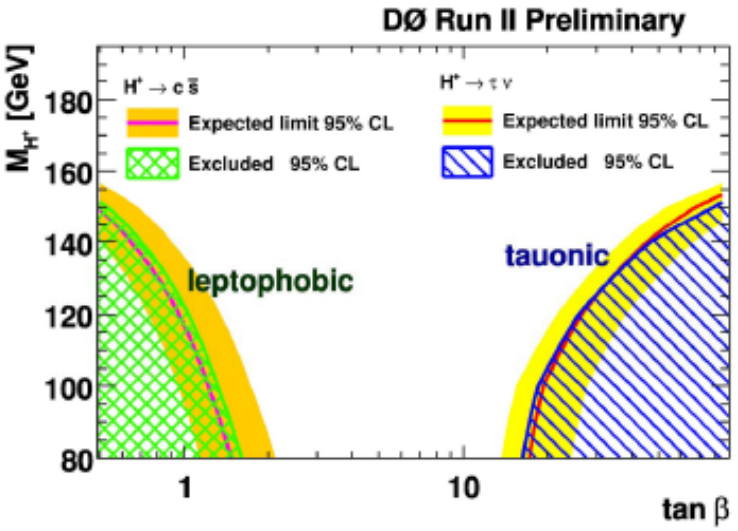
Beyond Standard Model

Charged Higgs

Decay Mode	Production	Method	Experiment	Luminosity
$H^{\pm} \to cs$	$t \to H^{\pm} b$	direct	CDF	2.2 fb^{-1}
$H^{\pm} \to \tau\nu$, qq	$t \to H^{\pm} b$	direct+indirect	DØ	1.0 fb^{-1}
$H^{\pm} \to tb$	$qq \to H^{\pm}$		DØ	0.9 fb^{-1}
$H^{\pm} \to \tau\nu$	$t \to H^{\pm} b$	direct	CDF	0.3 fb^{-1}

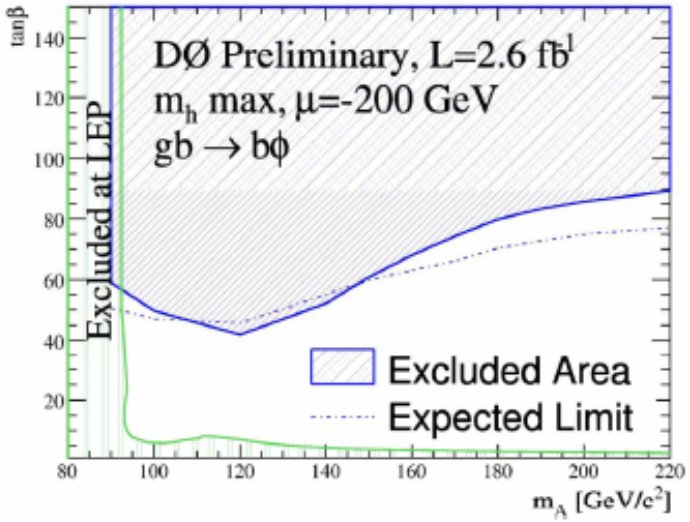


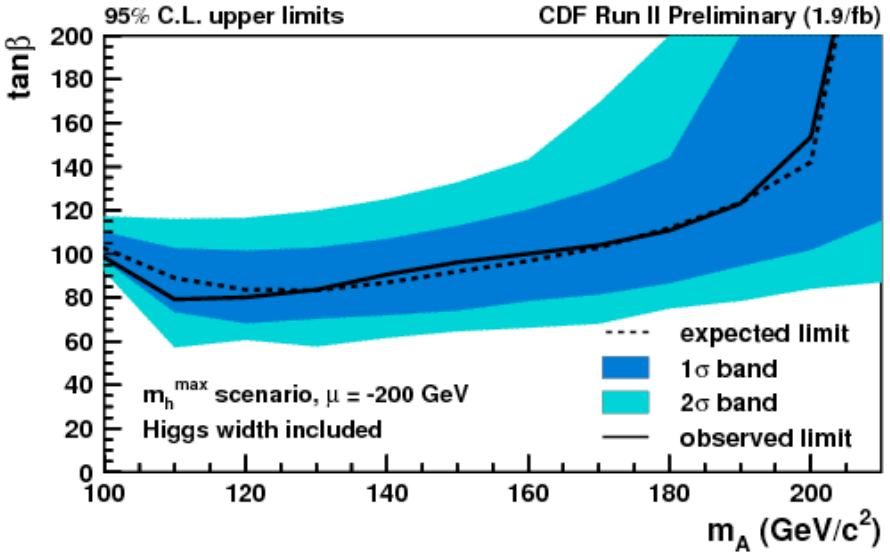
- Search in top-pair sample
- CDF
  - One high pt lepton, missing Et, >4 jets, b-tagging
  - Binned likelihood fit to dijet mass
- D0
  - Search top decays in dilepton, lepton+jets, lepton+tau
  - Binned likelihood to extract the expecte number of signal+background events, combining all channels



Neutral Higgs: $H \rightarrow b\bar{b} + b + (\bar{b})$

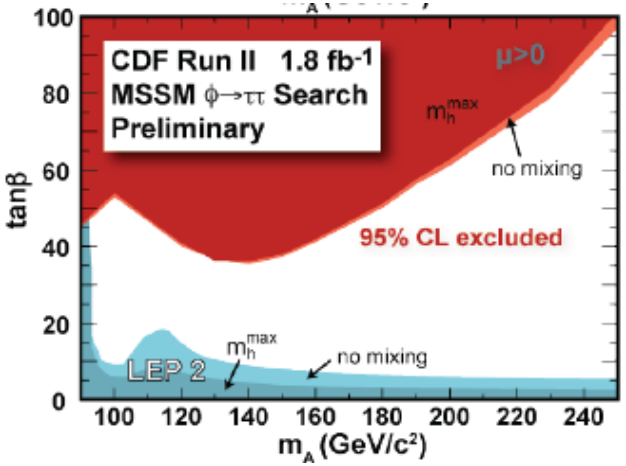
- 3 or more b-tagged jets
- CDF and D0
  - Search for peak in dijet mass spectra
- CDF
  - Binned maximum likelihood fit using Mjj
- D0
  - Train and cut on kinematic likelihood
  - Use Mjj to set limits

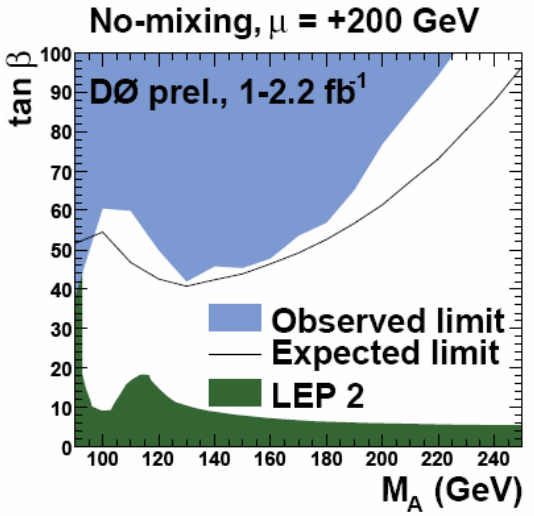


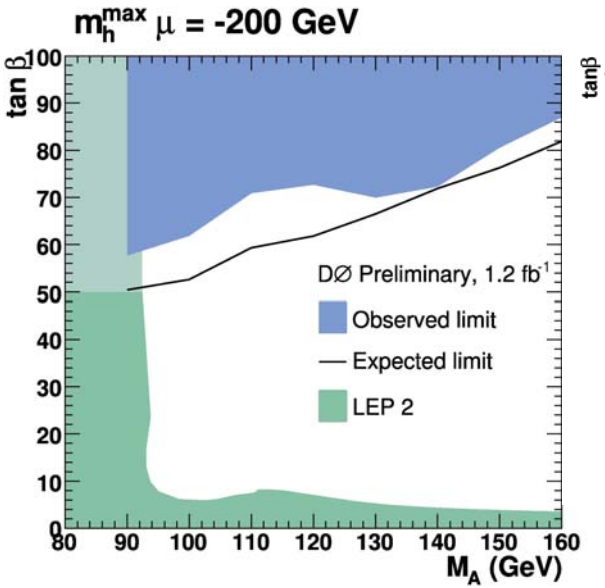


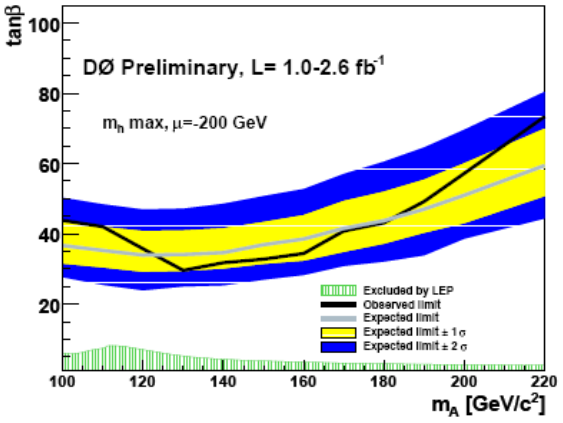
Neutral Higgs: $H \rightarrow \tau\tau$

- CDF and D0
  - 2 taus, leptonic+hadronic or e+μ
  - Likelihood fit based on visible mass distribution of di-taus (including missing E
  - All channels simultaneously fitted
- D0
  - Also $b\phi \rightarrow b\tau\tau$ used, same sensitivity
  - Search in μ+hadronic τ+one b-tagged jet at least
  - Cross section Limit determined by cut on 2D-distribution:
    - NN output used to reduce tt-bar background
    - log-likelihood to reduce QCD background





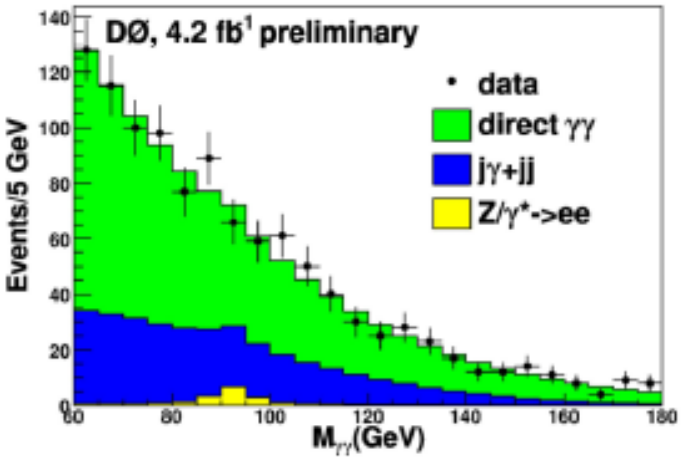


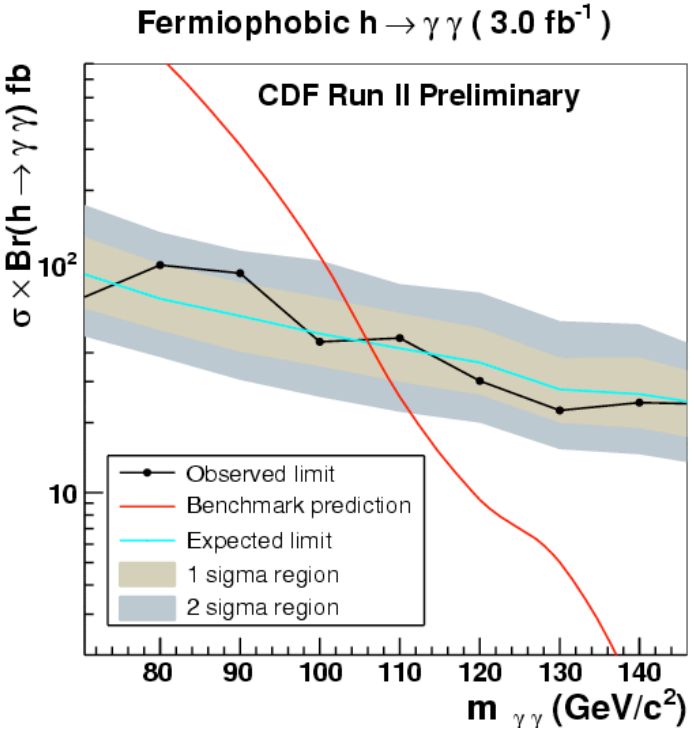


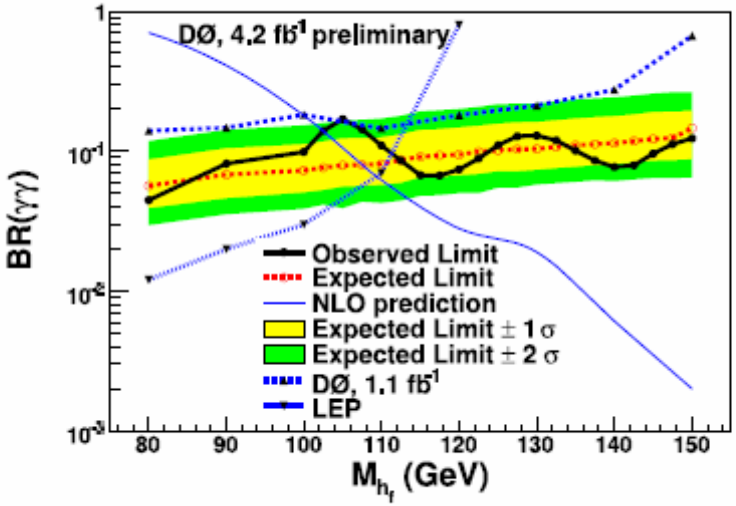
Combined ττ,bττ,bbb

Fermiophobic Higgs: $H \rightarrow \gamma\gamma$

- CDF and D0
  - 2 photons at least, high pt diphoton
  - Look for peak in diphoton mass
- CDF
  - Two photon central or One central + one endcap
  - $P_t^{\gamma\gamma} > 75$ GeV
- D0
  - Two photons central
  - $P_t^{\gamma\gamma} > 35$ GeV

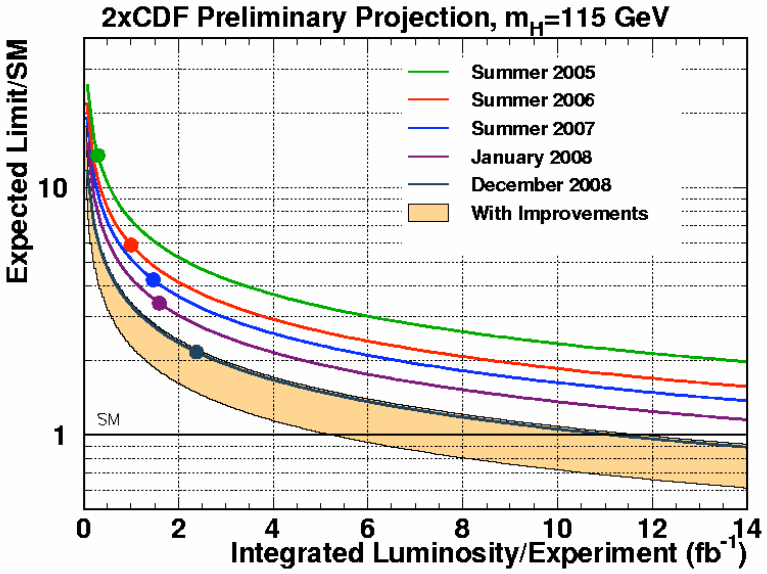


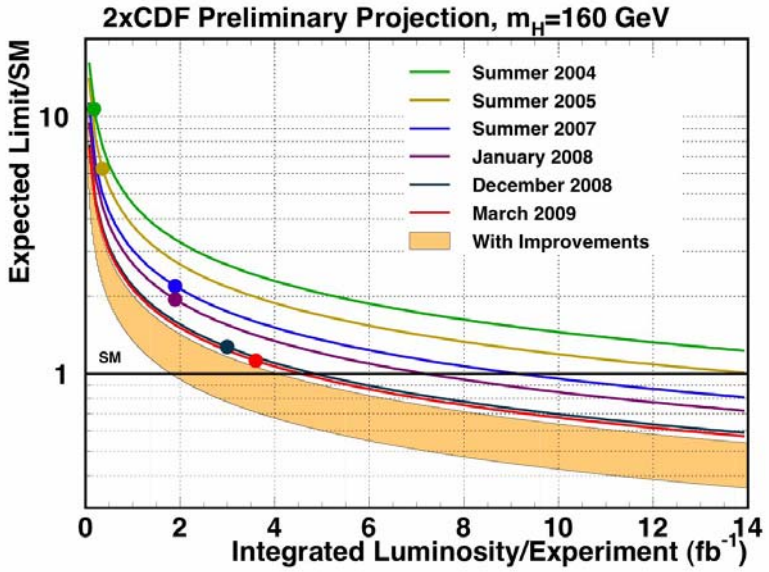




CONCLUSIONS AND PROSPECTS

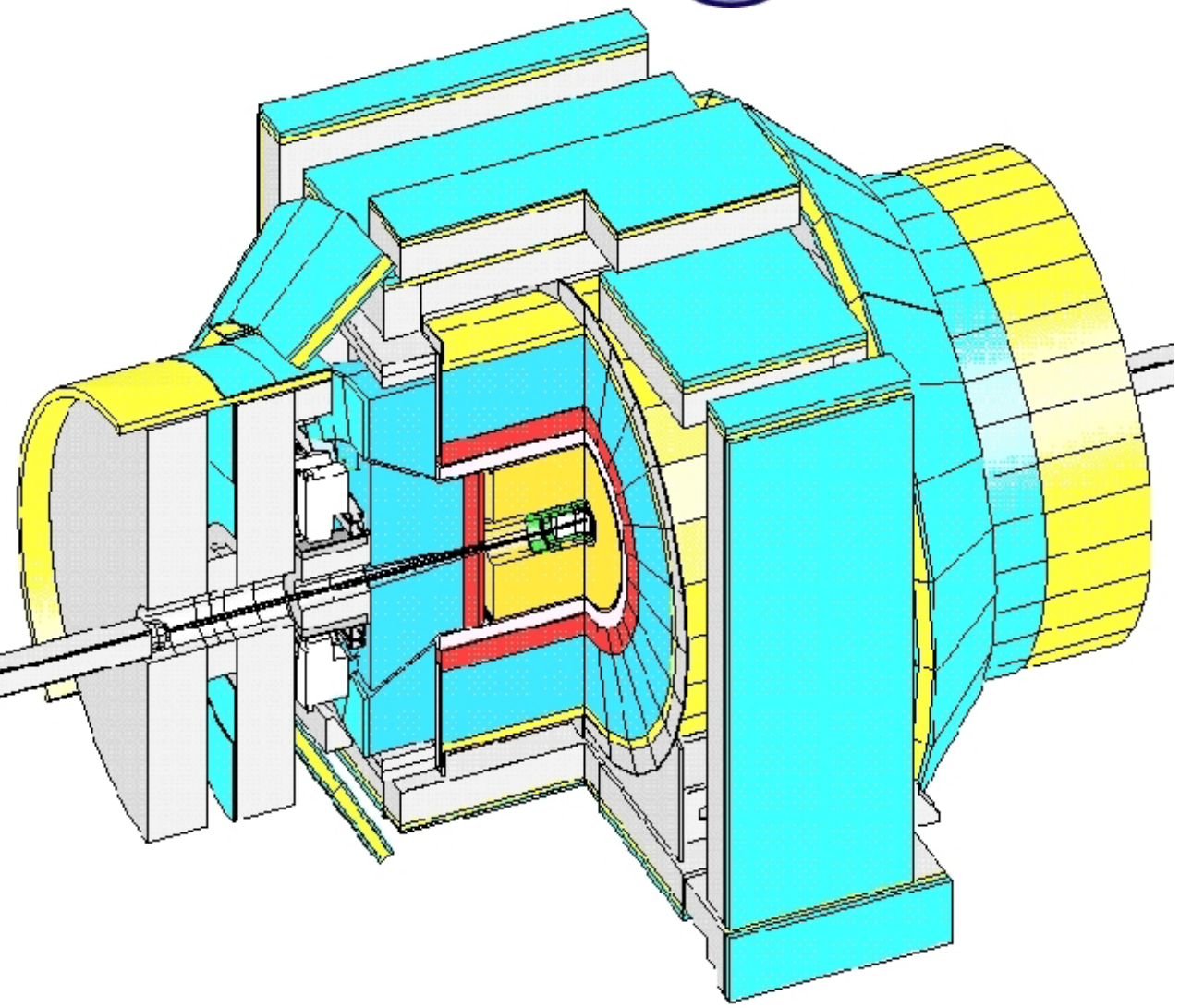
- Tevatron performing very well, high luminosity, stable
- New channels and analysis techniques improved, more acceptance
- Combined sensitivity is 2.36*SM, at M_H= 115 GeV, and 1.15*SM at 165 GeV
- 95%CL SM Higgs exclusion from 160-170 GeV
- No evidence of new particles





BACKUP

The CDF II Detector



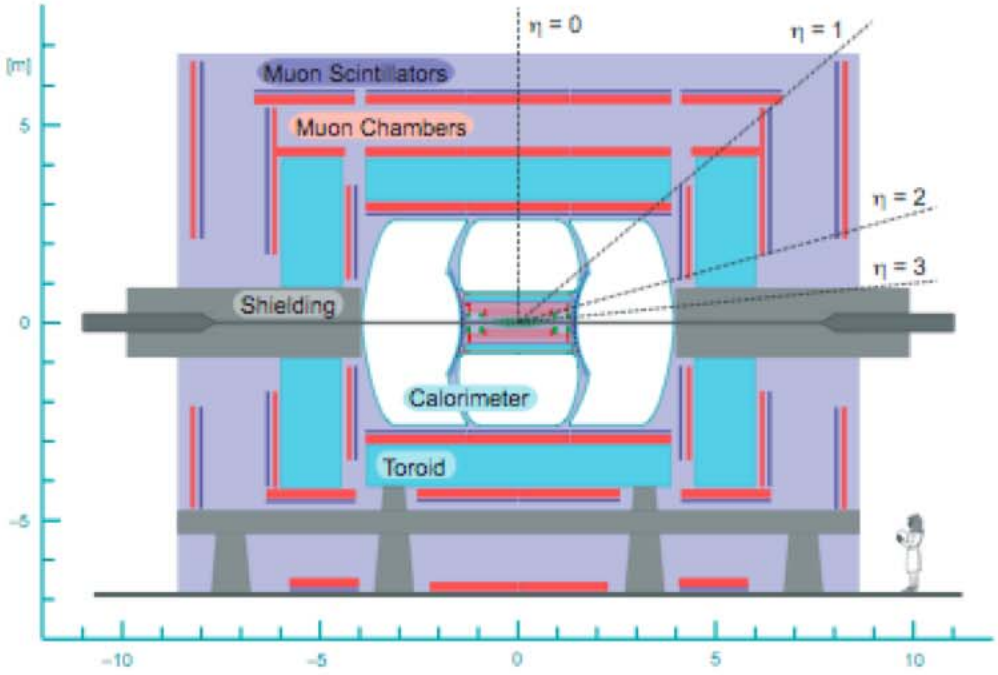
Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

b-tagging with
$|\eta| < \sim 1.4$

Jets to
$|\eta| < 2.8$
Higgs analyses restrict to
$|\eta| < 2.0$

Dijet mass resolution: ~16%

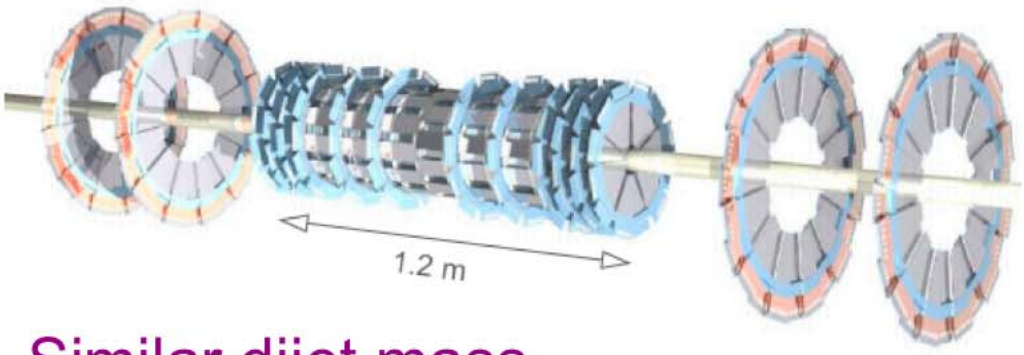
The DØ Detector



Lepton coverage:
$|\eta| < 2$ (muons)
$|\eta| < 2.6$ (electrons)

b-tagging with
$|\eta| < \sim 2$

Jets to
$|\eta| < 3$



Similar dijet mass resolution to CDF

New Innermost Silicon Layer added between Run IIa and Run IIb

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

$M_H = 160$ GeV/c^2			
$t\bar{t}$	136	±	23
DY	210	±	38
WW	421	±	46
WZ	38.9	±	5.3
ZZ	29.2	±	4.0
W+jets	189	±	48
$W\gamma$	110	±	29
Total Background	1134	±	110
$gg \to H$	15.9	±	2.3
WH	3.24	±	0.42
ZH	1.13	±	0.15
VBF	1.08	±	0.17
Total Signal	21.4	±	2.5
Data	1126		

OS+SS

WW

Process	Exclusive 1Tag	ST+ST	ST+JP
QCD + Mistags	941 ± 44	42.1 ± 8.7	78 ± 11
Single Top	43.2 ± 7.9	8.5 ± 1.7	7.2 ± 1.5
Top Pair	124 ± 17	27.4 ± 4.3	27.1 ± 4.6
Di-boson	35.6 ± 6.8	4.9 ± 1.2	4.3 ± 1.1
W + h.f.	297 ± 130	11.0 ± 6.5	21 ± 11
Z + h.f.	107 ± 46	10.8 ± 5.0	11.3 ± 5.2
Total Exp	1548 ± 146	105 ± 13	149 ± 17
Observed	1443	105	148
$ZH \to \nu\nu bb$ (MH115GeV)	2.1	1.0	0.8
$WH \to (l)\nu bb$ (MH115GeV)	1.8	0.9	0.7
$ZH \to (ll)bb$ (MH115GeV)	0.09	0.04	0.03

Number of expected and observed events in the Signal Region in all tagging categori

ZH

Source	ee	$\mu\mu$	ll
$Z \to ee$	70.7 ± 18.8	0.0 ± 0.0	70.7 ± 18.8
$Z \to ee + hf$	63.0 ± 11.4	0.0 ± 0.0	63.0 ± 11.4
$Z \to \mu\mu$	0.0 ± 0.0	58.9 ± 14.9	58.9 ± 14.9
$Z \to \mu\mu + hf$	0.0 ± 0.0	44.2 ± 8.1	44.2 ± 8.1
$Z \to \tau\tau$	0.1 ± 0.1	0.0 ± 0.1	0.1 ± 0.1
$Z \to \tau\tau + hf$	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1
WW, WZ, ZZ	6.6 ± 1.0	5.0 ± 0.8	11.6 ± 1.3
Fakes	12.8 ± 6.4	3.1 ± 1.2	15.9 ± 6.5
$t\bar{t}$	7.7 ± 1.5	6.2 ± 1.2	13.9 ± 2.0
$ZH(m_H = 115$ GeV/$c^2)$	0.7 ± 0.1	0.5 ± 0.1	1.3 ± 0.2
Total	161.6 ± 23.0	117.9 ± 17.1	279.5 ± 28.6
Data	152	106	258

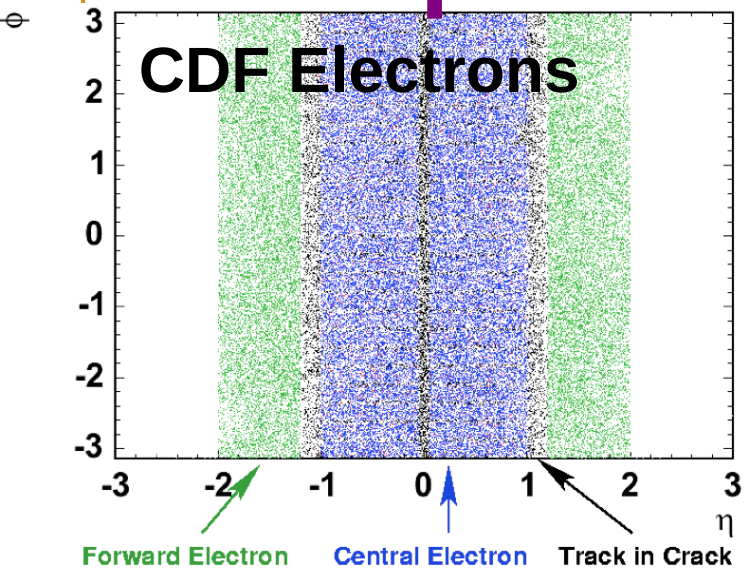
TABLE I: The number of signal events expected to be accepted by our selection, the SM prediction for $\sigma \times \mathcal{B}(H \to b\bar{b})$, and the expected and observed limits at 95% C.L. on the Higgs boson production cross section relative to the SM value as shown in Fig. 2. The expected limits are also included for the NN and MEBDT analyses individually.

Mass (GeV/c^2)	100	105	110	115	120	125	130	135	140	145	150
Exp. signal (events)	12.8	11.7	10.3	8.6	6.9	5.6	4.3	3.1	2.1	1.4	0.9
SM $\sigma \times \mathcal{B}(H \to b\bar{b})$ (fb)	232	201	169	136	104	83	63	45	30	20	12
Exp. NN (95% C.L./SM)	4.3	4.6	5.0	5.8	6.9	8.2	10.0	13.8	19.4	28.9	43.2
Exp. MEBDT (95% C.L./SM)	3.8	4.0	4.5	5.2	6.3	8.0	10.0	13.4	19.2	27.0	48.7
Exp. combination (95% C.L./SM)	3.5	3.8	4.1	4.8	5.9	7.2	8.7	12.2	17.5	25.6	40.5
Observed (95% C.L./SM)	3.3	3.6	4.9	5.6	5.9	8.0	8.9	13.2	26.5	42.1	75.5

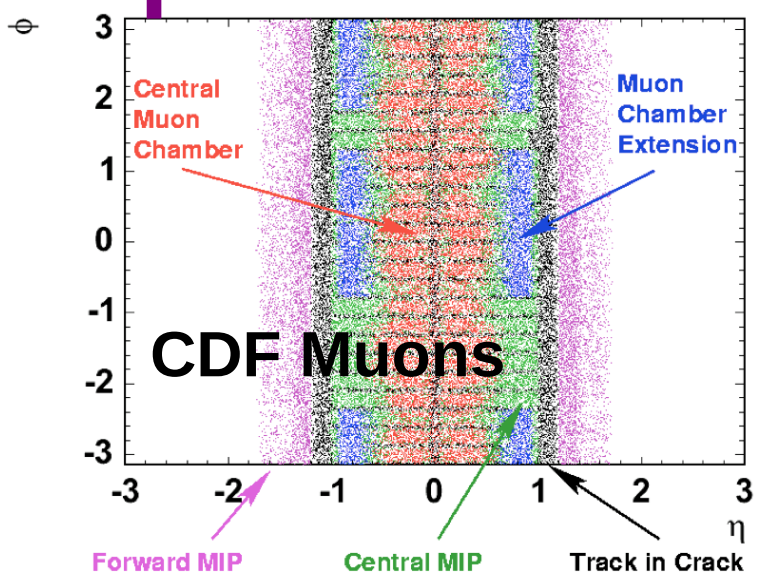
ZH_ 1tightTag_ME

WH

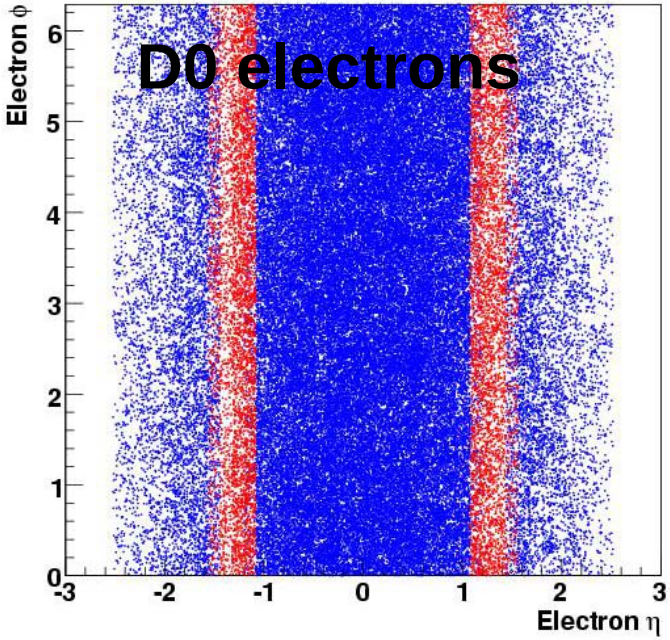
Lepton Acceptance Gains



10% gain in CDF electron acceptance



30% gain in CDF single-muon acceptance



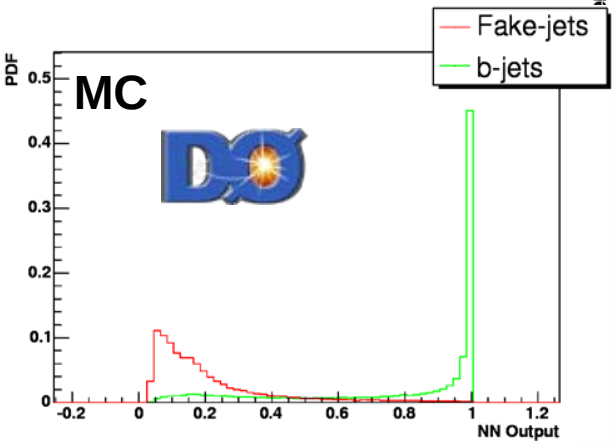
Inter-calorimeter electrons
-- 10% gain in D0 electron acceptance

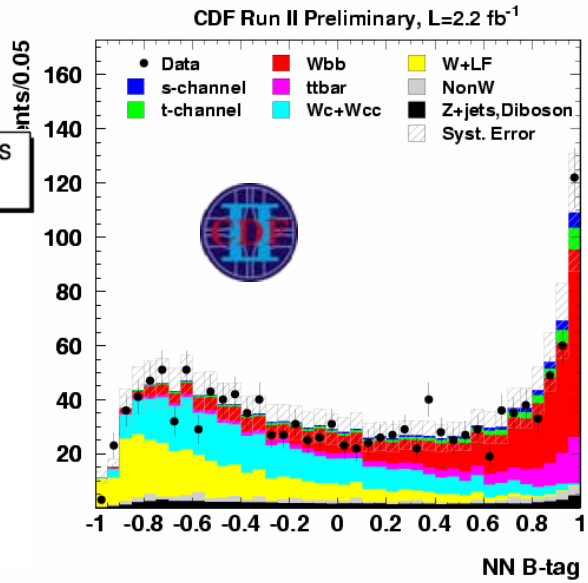
For di-lepton events, trigger lepton has tighter requirements than the other one. For single-lepton analyses, need other triggers like MET+jets

Neural Networks for Better B-tagging

CDF: Train a NN to separate b's from charm and light flavor jets in vertex-tagged jets

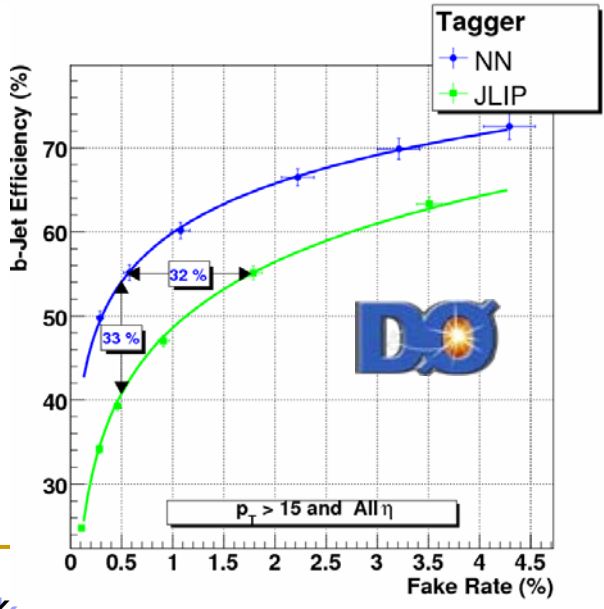
D0: Use the NN as the b-tagging tool from the start. Choice of operating points.





Some of the inputs:

- Displaced vertex mass
- # tracks in displaced vertex
- Decay flight distance and significance
- Identified leptons in and near jets
- Secondary vertex fit χ^2
- Jet E_T



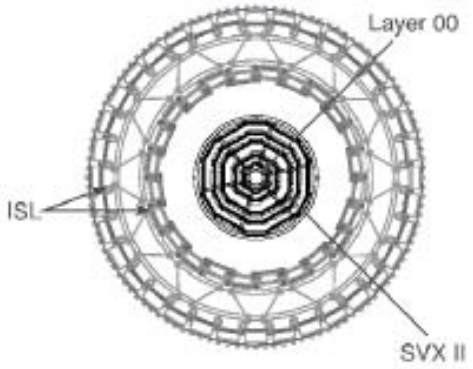
CDF and D0: Efficiency and Mistags and NN's Calibrated with Data

- Jet samples with vertex and soft-lepton tags
- Negative tags.

Tag rates parameterized with E_T, η

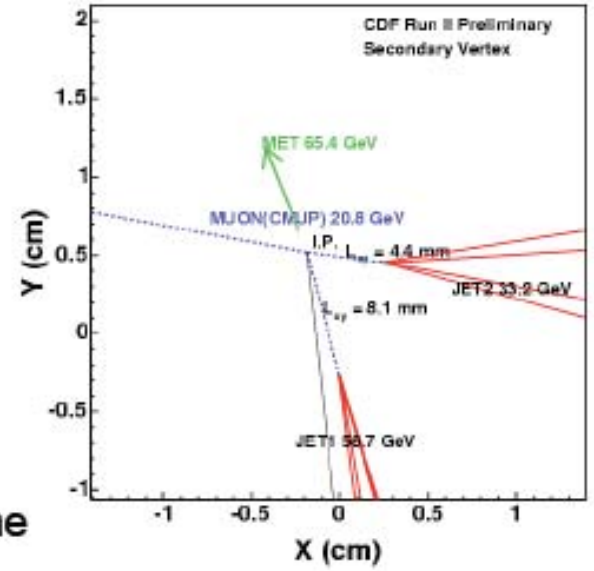
B-Tagging

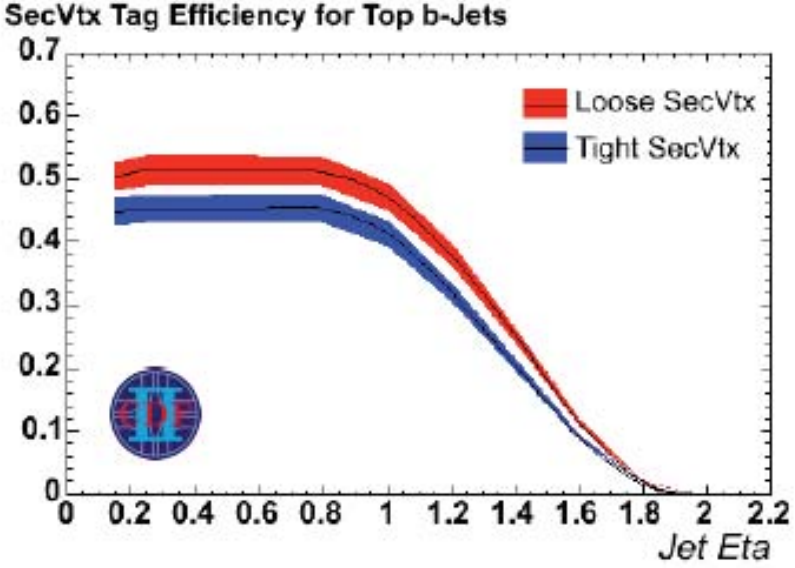
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm

B-tagging relies on displaced vertex reconstruction:
high mass, long lifetime





Mistag rates typically ~1% for light-flavor jets

Example candidate event (lvbb)

D0 B-tagging per-jet efficiency = 50-70% (of taggable jets) for 1-5% Mistag rate

Tevatron Correlated systematics

- Total systematic error count : 109 (not counting bin-by-bin errors)
- Note: correlations in errors on backgorund betwen experiments helps sensitivity One experiment is another exp. control sample
- Luminosity: 3.8% correlated CDF and D0 from σ_{inel} *(ppbar)*, 4.4% detector specific
- Diboson Cross sections (6% relative uncertainty)
- *tt* cross section: Moch and Uwer, evaluated at m_t = 172.4 ± 1.2 GeV
- $\sigma(tt)$= 7.79 pb with a 10% systematic uncertainty.
- Signal Cross sections: *VH* is 5%, *gg* → *H* is 12% and VBF is 10%

- CDF-D0 uncorrelated errors but correlated within the experiments where
- appropriate:
  - k-factors (data driven)
  - trigger efficiencies
  - b-tag efficiencies and mistags
  - jet energy scale
  - lepton id.fakes and conversions
  - MET modeling

Tom Junk

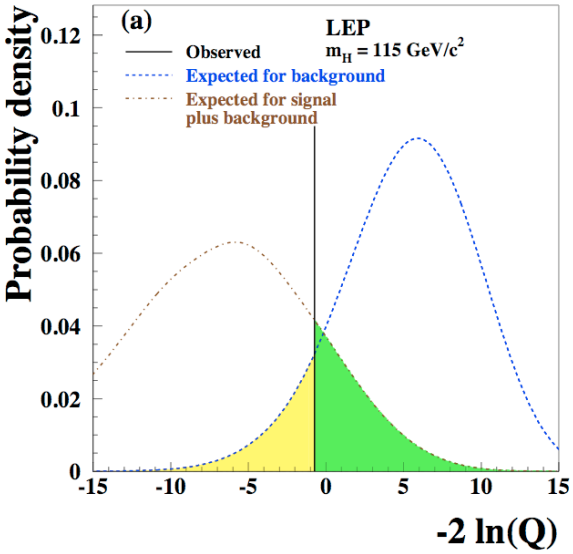
Tom Junk

Higgs Boson Production Cross Sections and Branching Ratios

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$B(H \to b\bar{b})$ (%)	$B(H \to \tau^+\tau^-)$ (%)	$B(H \to W^+W^-)$ (%)
100	1861	286.1	166.7	99.5	81.21	7.924	1.009
105	1618	244.6	144.0	93.3	79.57	7.838	2.216
110	1413	209.2	124.3	87.1	77.02	7.656	4.411
115	1240	178.8	107.4	79.07	73.22	7.340	7.974
120	1093	152.9	92.7	71.65	67.89	6.861	13.20
125	967	132.4	81.1	67.37	60.97	6.210	20.18
130	858	114.7	70.9	62.5	52.71	5.408	28.69
135	764	99.3	62.0	57.65	43.62	4.507	38.28
140	682	86.0	54.2	52.59	34.36	3.574	48.33
145	611	75.3	48.0	49.15	25.56	2.676	58.33
150	548	66.0	42.5	45.67	17.57	1.851	68.17
155	492	57.8	37.6	42.19	10.49	1.112	78.23
160	439	50.7	33.3	38.59	4.00	0.426	90.11
165	389	44.4	29.5	36.09	1.265	0.136	96.10
170	349	38.9	26.1	33.58	0.846	0.091	96.53
175	314	34.6	23.3	31.11	0.663	0.072	95.94
180	283	30.7	20.8	28.57	0.541	0.059	93.45
185	255	27.3	18.6	26.81	0.420	0.046	83.79
190	231	24.3	16.6	24.88	0.342	0.038	77.61
195	210	21.7	15.0	23	0.295	0.033	74.95
200	192	19.3	13.5	21.19	0.260	0.029	73.47

gg→H from Grazzini and de Florian, similar to those of other authors

Mini-Review: CL_s Limits



p-values:

Yellow area = $1\text{-}CL_b = 1\text{-}P(-2\ln Q > -2\ln Q_{obs} |\ b\ \text{only})$

Green area = $CL_{s+b} = P(-2\ln Q > -2\ln Q_{obs} |\ s+b)$

$CL_s \equiv CL_{s+b}/CL_b \geq CL_{s+b}$

Exclude if $CL_s < 0.05$

Vary r until $CL_s = 0.05$ to get r_{lim}

- Advantages:
  - Exclusion and Discovery p-values are consistent.
    Example -- a 2σ upward fluctuation of the data with respect to the background prediciton appears both in the limit and the p-value as such
  - Does not exclude where there is no sensitivity
    (big enough search region with small enough resolution and you get a 5% dusting of random exclusions with CL_{s+b})

Tom Junk

Tom Junk

Bayesian Posterior Probability

$$p(R|\vec{n}) = \frac{\int\int d\vec{s}d\vec{b}L(R,\vec{s},\vec{b}|\vec{n})\pi(R,\vec{s},\vec{b})}{\int\int\int dRd\vec{s}d\vec{b}L(R,\vec{s},\vec{b}|\vec{n})\pi(R,\vec{s},\vec{b})} \Rightarrow \int_0^{R_{0.95}} p(R|\vec{n})dR = 0.95$$

$R = (\sigma \times BR)/(\sigma_{SM} \times BR_{SM})$, $R_{0.95}$: 95% Credible Level Upper Limit

$\vec{s},\vec{b},\vec{n} = s_{ij}, b_{ij}, n_{ij}$(# of signal, background and observed events in j-th bin for i-th channel)

π : Bayes' prior density

Combined Binned Poisson Likelihood

$$L(R,\vec{s},\vec{b}|\vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

Principle of ignorance

- for the number of higgs events (instead of higgs Xsec)

$$\pi(R,\vec{s},\vec{b}) = \pi(R)\pi(\vec{s})\pi(\vec{b}) = s_{tot}\theta(Rs_{tot})\pi(\vec{s})\pi(\vec{b})$$

$s_{tot} = \Sigma_{i,j} s_{ij}$: Total number of signal prediction

$\pi(x) = G(x|\hat{x},\sigma_x)$ $(x = s, b)$ $\hat{x}$: expected mean, σ_x: total uncertainty

Mini-Review: Bayesian Limits

$$L(r,\theta) = \prod_{channels} \prod_{bins} P_{Poiss}(data \mid r,\theta)$$

Where r is an overall signal scale factor, and θ represents all nuisance parameters.

$$P_{Poiss}(data \mid r,\theta) = \frac{(rs_i(\theta) + b_i(\theta))^{n_i}\, e^{-(rs_i(\theta)+b_i(\theta))}}{n_i!}$$

where n_i is observed in each bin i, s_i is the predicted signal for a fiducial model (SM), and b_i is the predicted background. Dependence of s_i and b_i on θ includes rate, shape, and bin-by-bin independent uncertainties.

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Mini-Review: Bayesian Limits

Including uncertainties on nuisance parameters θ

$$L'(data \mid r) = \int L(data \mid r, \theta)\pi(\theta)d\theta$$

where $\pi(\theta)$ encodes our prior belief in the values of the uncertain parameters. Usually Gaussian centered on the best estimate and with a width given by the systematic. Includes rate uncertainites, shape uncertainites, MC statistics in each bin.

$$0.95 = \int_0^{r_{\lim}} L'(data \mid r)\pi(r)dr$$

Sensitivity = Median Expected Limit

- Run simulated background-only MC pseudoexperiments (fluctuate all systematics)
- Compute r_{lim} for each one; find medain and $\pm 1,2\sigma$ variations.

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Tevatron Combined Higgs Limits -- By the Numbers

Bayesian	100	105	110	115	120	125	130	135	140	145	150
Expected	2.0	2.0	2.2	2.4	2.7	2.9	2.9	2.7	2.5	2.4	1.8
Observed	1.9	1.8	2.4	2.5	2.8	3.0	3.5	2.4	2.7	2.8	1.9

CL_S	100	105	110	115	120	125	130	135	140	145	150
Expected	1.9	1.9	2.1	2.4	2.6	2.7	2.9	2.7	2.5	2.2	1.8
Observed	1.7	1.7	2.2	2.6	2.8	2.9	4.0	2.6	3.1	2.8	2.0

Bayesian	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.4	1.6	1.9	2.2	2.7	3.5	4.2
Observed	1.4	0.99	0.86	0.99	1.1	1.2	1.7	2.0	2.6	3.3

CL_S	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.3	1.6	1.8	2.5	3.0	3.5	3.9
Observed	1.3	0.95	0.81	0.92	1.1	1.3	1.9	2.0	2.8	3.3

For details, see arXiv:0903.4001 [hep-ex]

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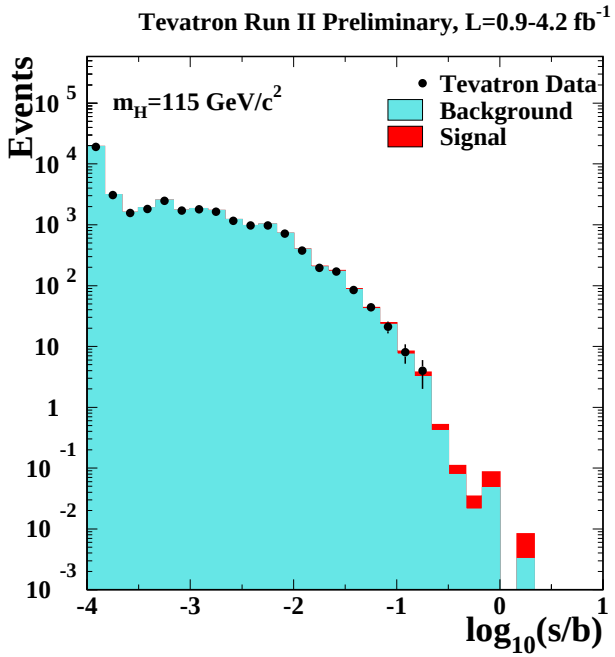
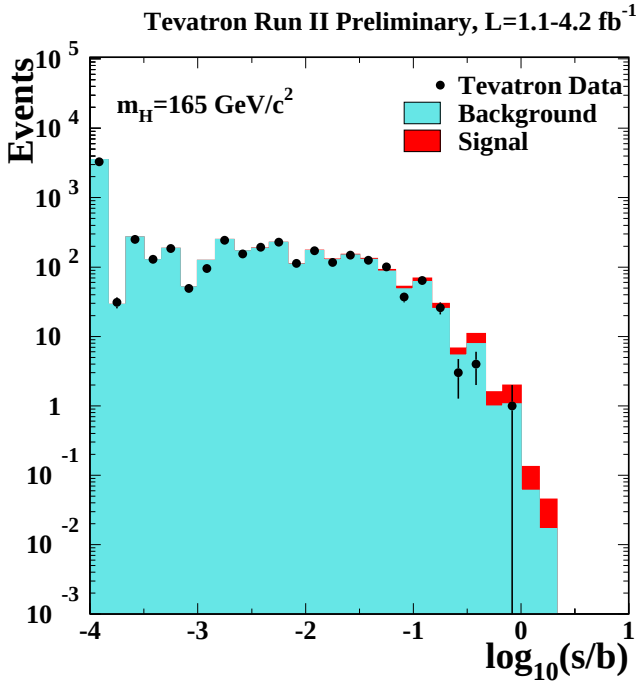
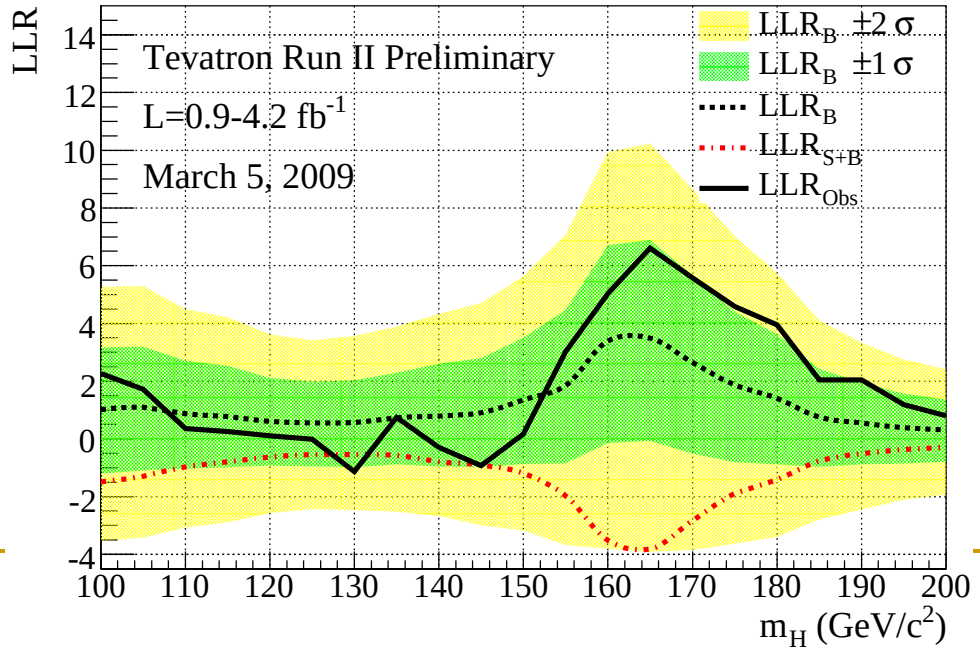
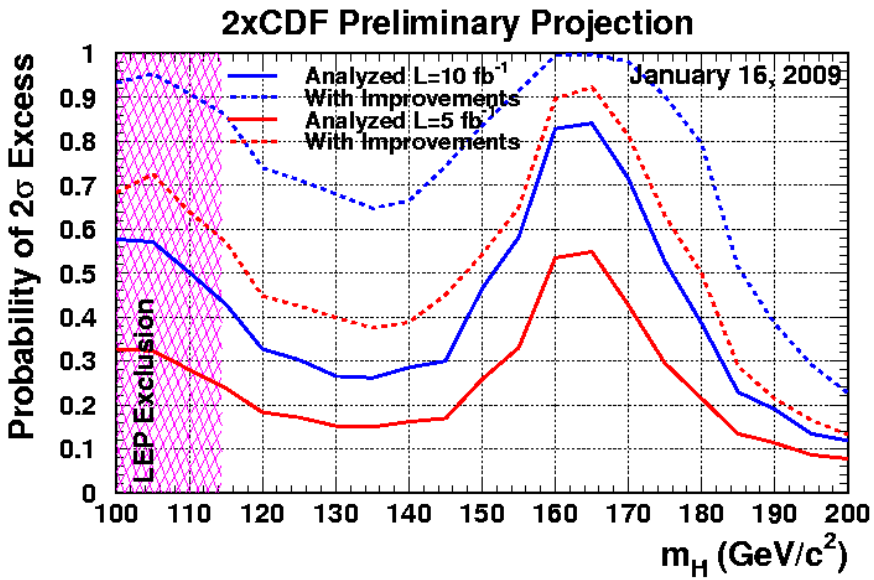
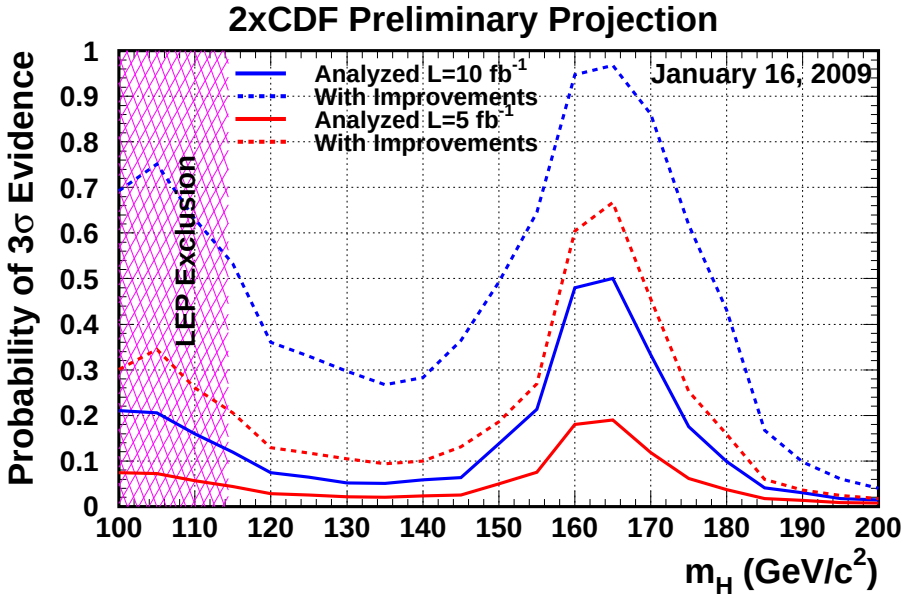

Tevatron Run II Preliminary, L=0.9-4.2 fb-1
mH=115 GeV/c2
Tevatron Data
Background
Signal
Events
log10(s/b)


Tevatron Run II Preliminary, L=1.1-4.2 fb-1
mH=165 GeV/c2
Tevatron Data
Background
Signal
Events
log10(s/b)


Tevatron Run II Preliminary
L=0.9-4.2 fb-1
March 5, 2009
LLRB ±2 σ
LLRB ±1 σ
LLRB
LLRS+B
LLRObs
LLR
mH (GeV/c2)


2xCDF Preliminary Projection
Probability of 2σ Excess
Analyzed L=10 fb-1
With Improvements
Analyzed L=5 fb-1
With Improvements
January 16, 2009
LEP Exclusion
mH (GeV/c2)


2xCDF Preliminary Projection
Probability of 3σ Evidence
Analyzed L=10 fb-1
With Improvements
Analyzed L=5 fb-1
With Improvements
January 16, 2009
LEP Exclusion
mH (GeV/c2)