Higgs Searches at the Tevatron

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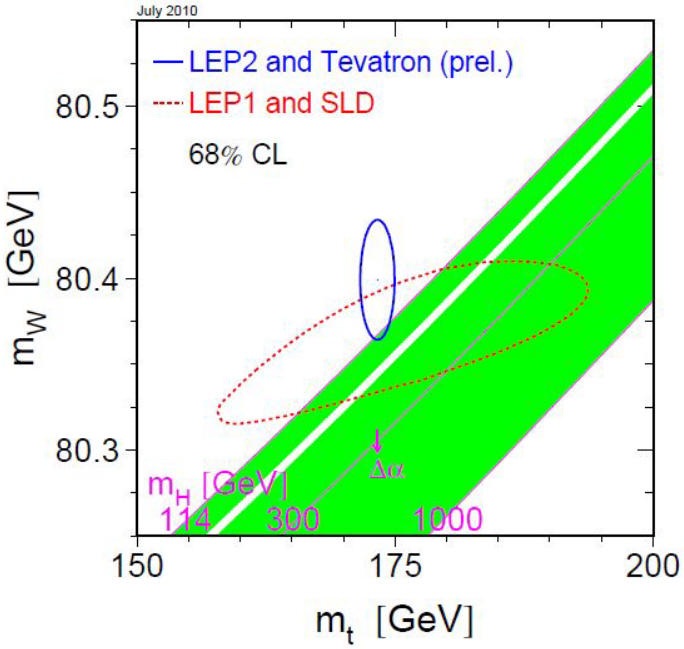
on behalf of the CDF and D0 Collaborations

What do we know about the Higgs?

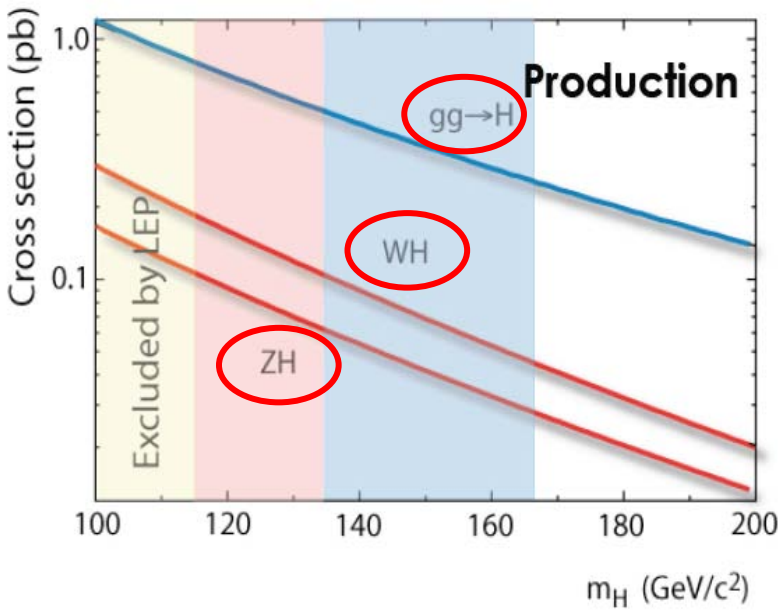
Predicted by one of the mechanisms of the EW symmetry breaking
Generates (non-zero) masses for the fermions and for the intermediate bosons
The only missing piece of the SM

Theoretical predictions via radiative corrections: $M_H = 89^{+35}_{-26}$ GeV (<158 GeV @ 95% CL)
Direct searches at LEP (200 GeV e^+e^- collider) $114 < M_H < 185$ GeV @ 95% CL

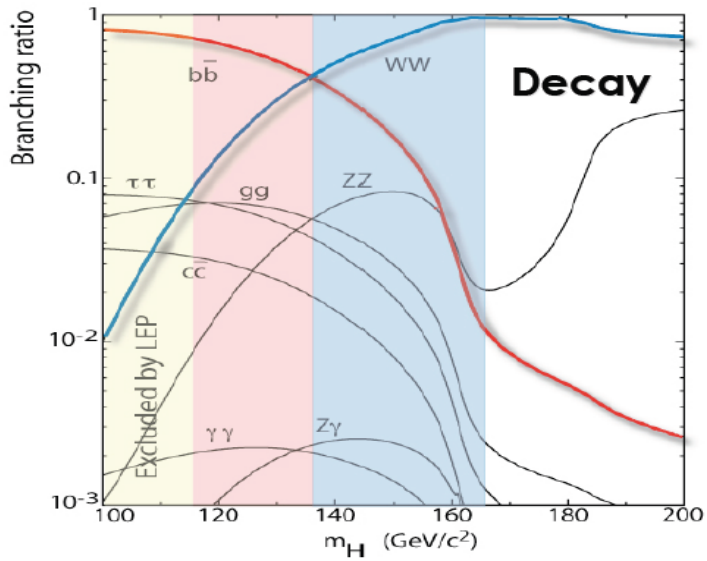


The Higgs boson is accessible
at the Tevatron

Main productions at the Tevatron…

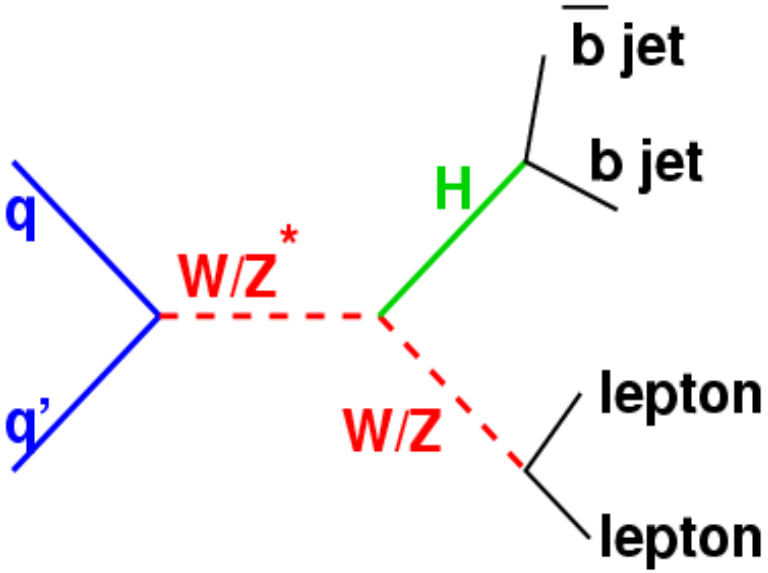


…and main decay modes

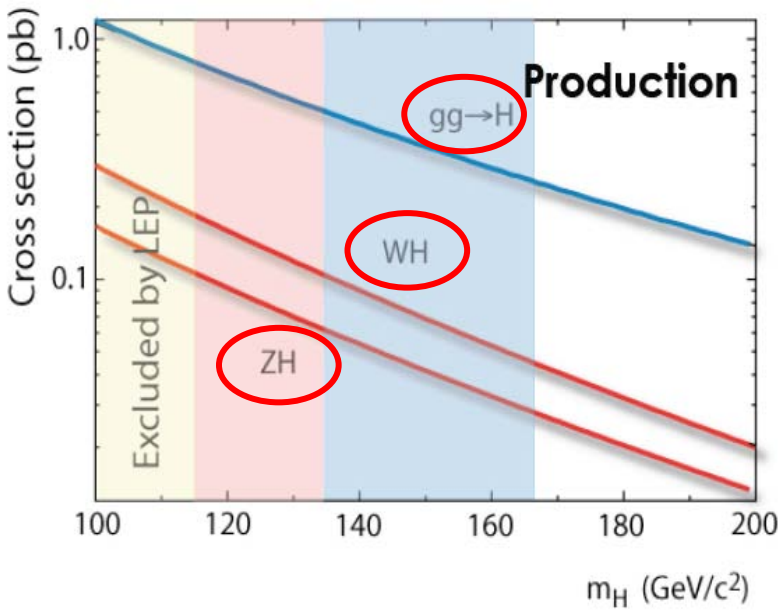


One looks for W/Z bosons in the final state to avoid QCD produced bb background

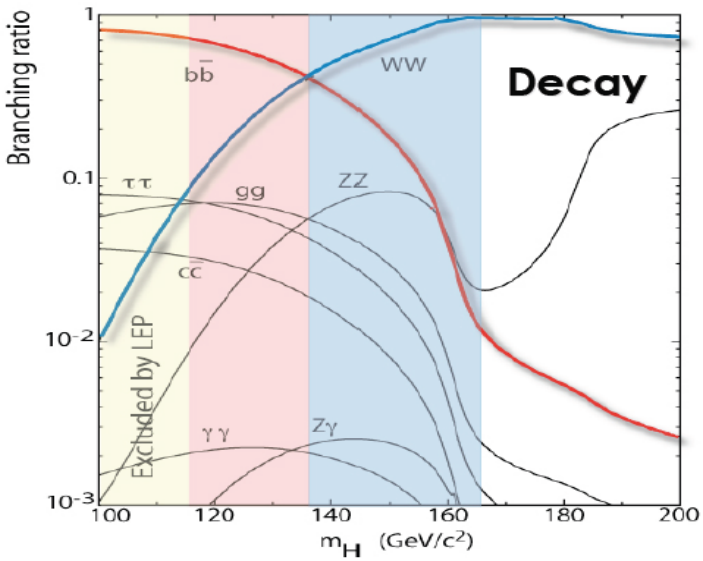
At low masses (M_H<135 GeV) bb channel produced by Higgs-Strahlung



Main productions at the Tevatron…

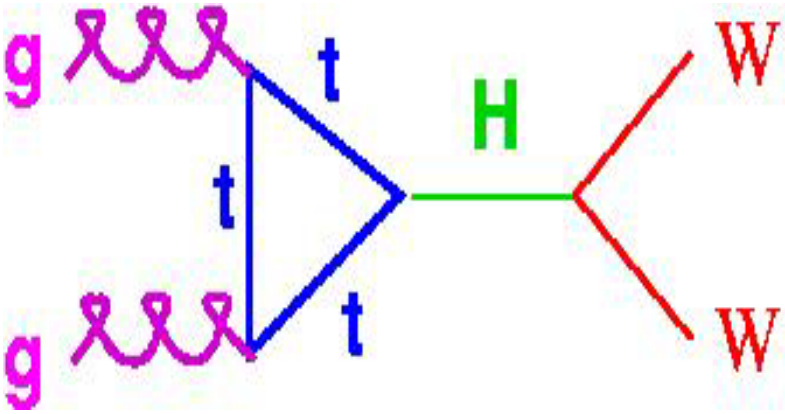


…and main decay modes



One looks for W/Z bosons in the final state to avoid QCD produced bb background

At high masses (M_H>135 GeV) W W channel produced by gg fusion



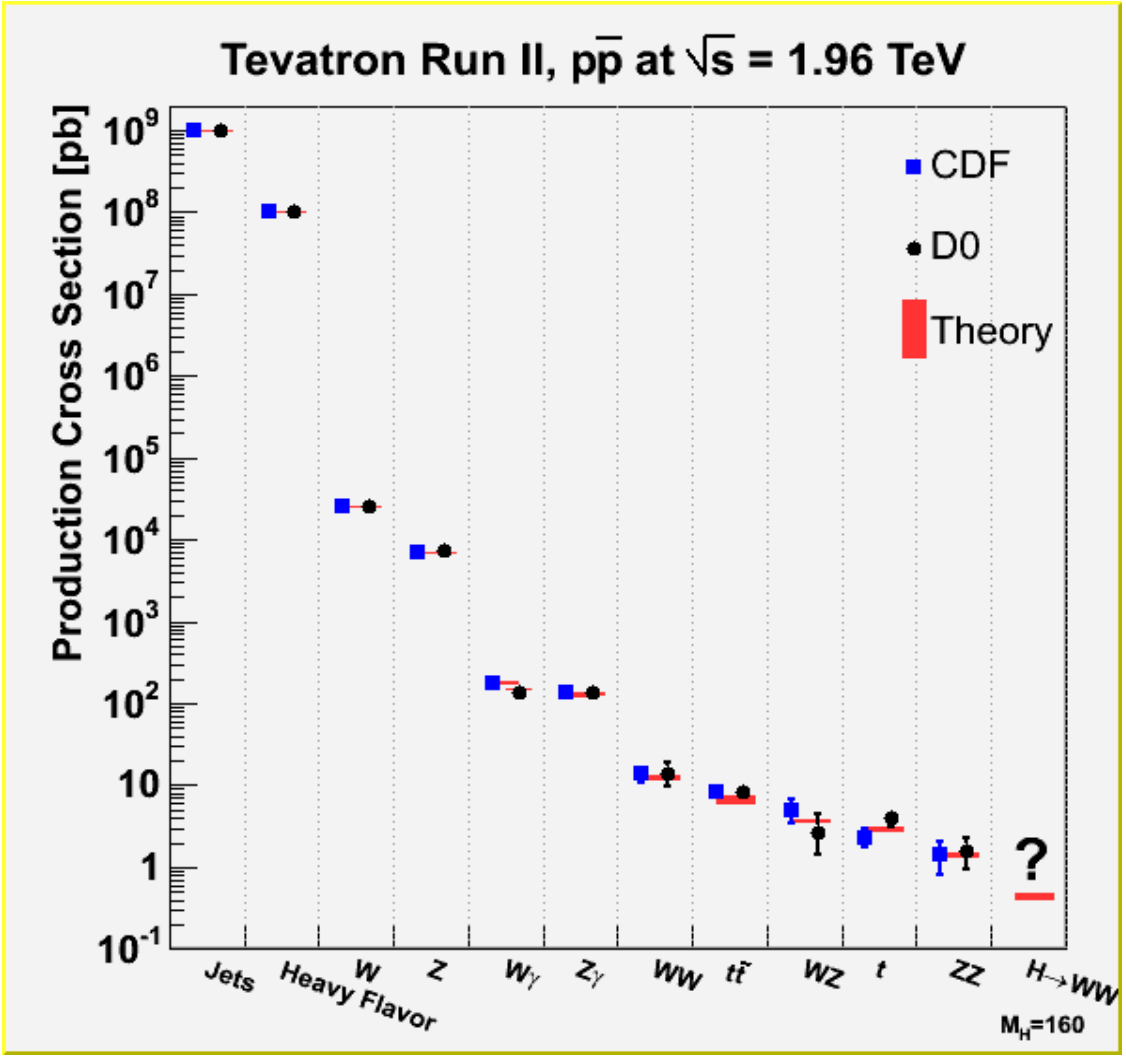
What can hide the Higgs?

Typical Higgs σ x BR < 1 pb

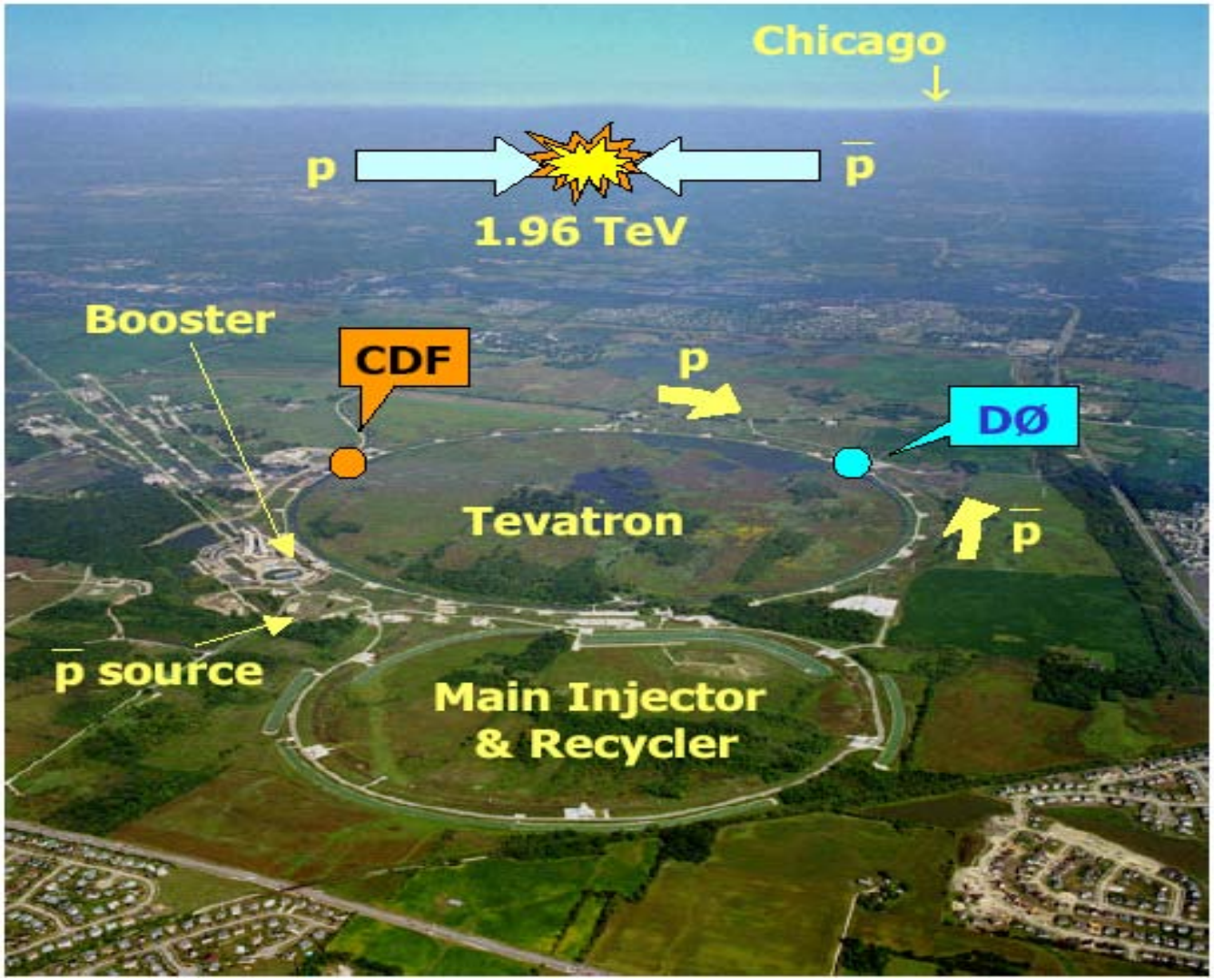
It is hidden by ~ 10^9 x larger background

All important SM backgrounds:
W/Z+jets (including HF)
single and double top production,
diboson (WW,WZ,ZZ) production
has been seen and measured

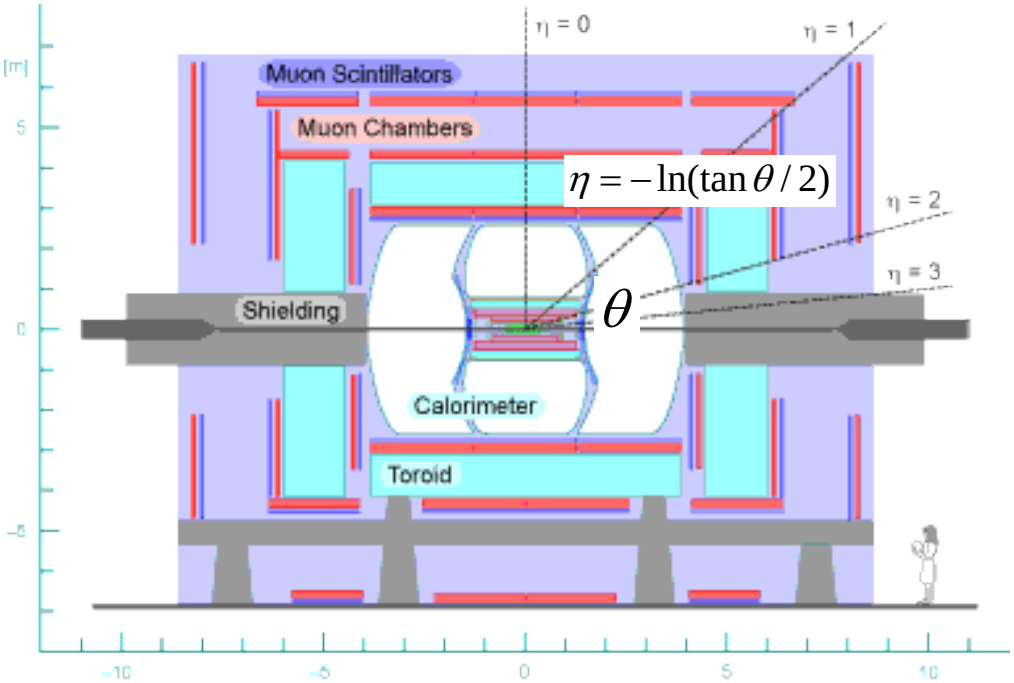
Last benchmark before detecting the Higgs is still to come
W Z / Z Z → W / Z (Z→) bb
hopefully soon



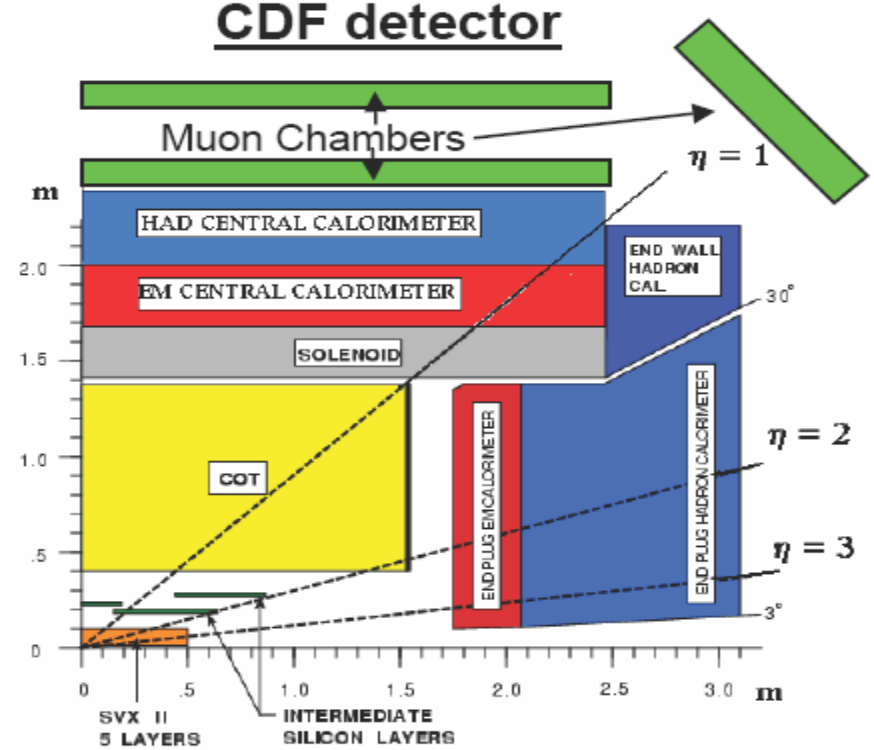
The Tevatron



D0 detector



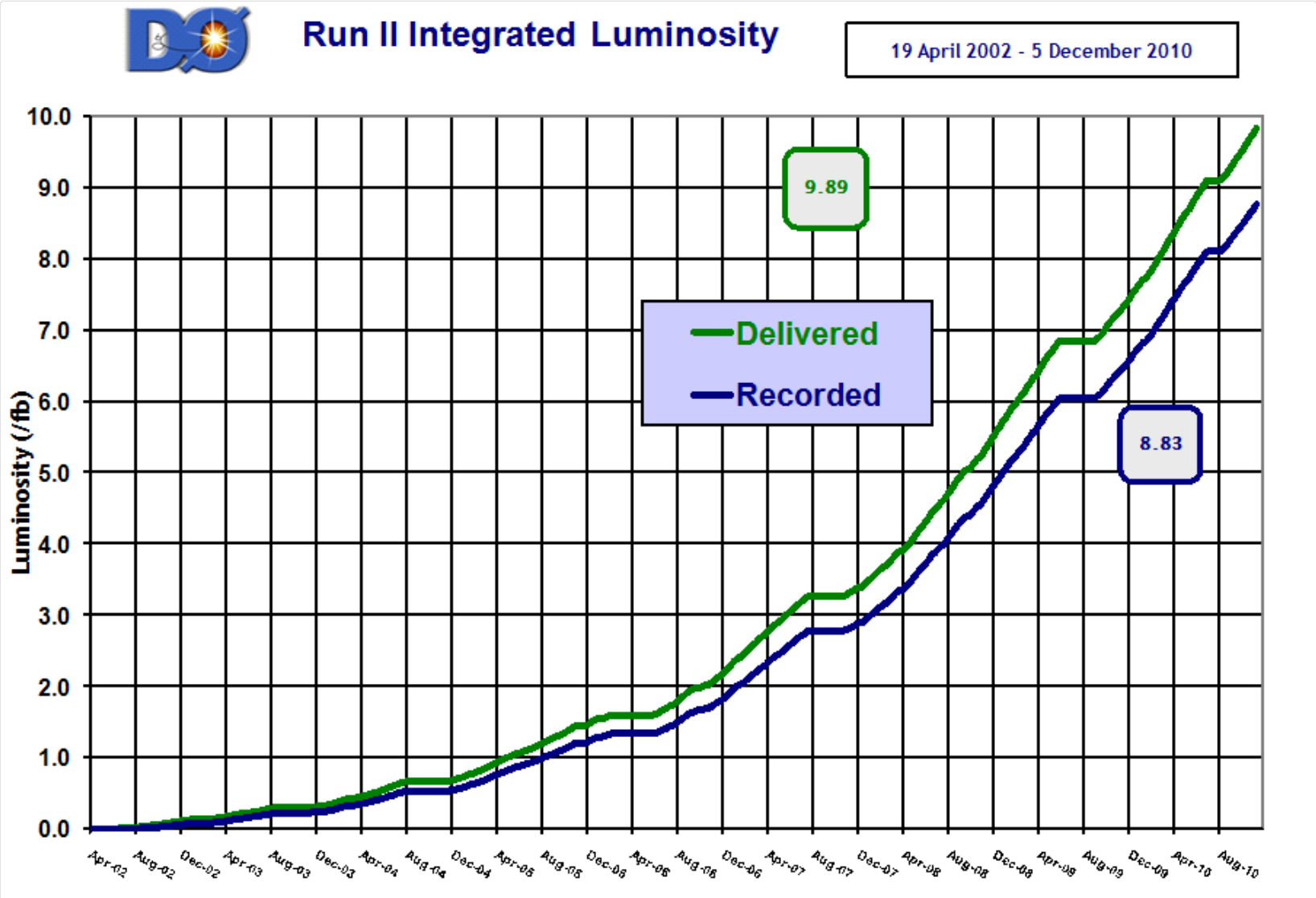
CDF detector



Both detectors have similar structure
with different particular advantages

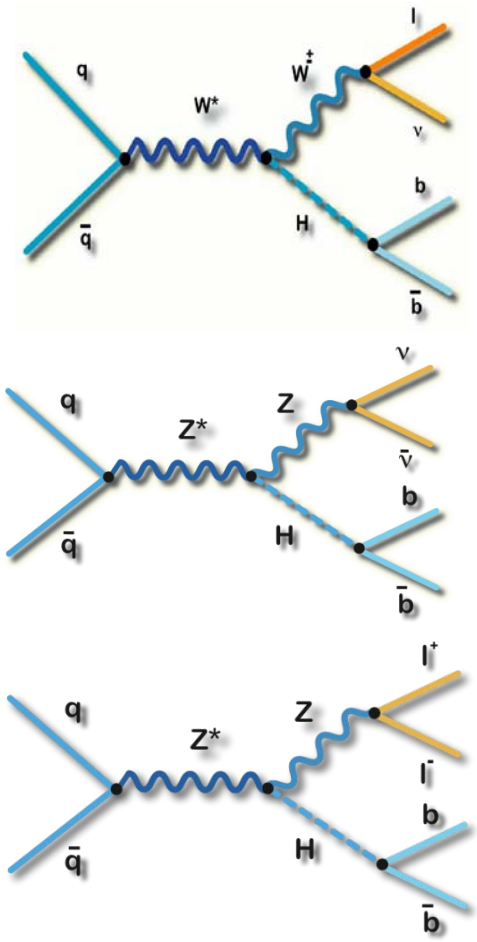
Hermetic LAr calorimeter
Muon detector with large coverage
in iron toroid

Central tracking system
with large lever arm



Present talk includes analyses with upto 6.7 fb^{-1} data

The main final states for $M_H < 135$ GeV (Higgs Strahlung)



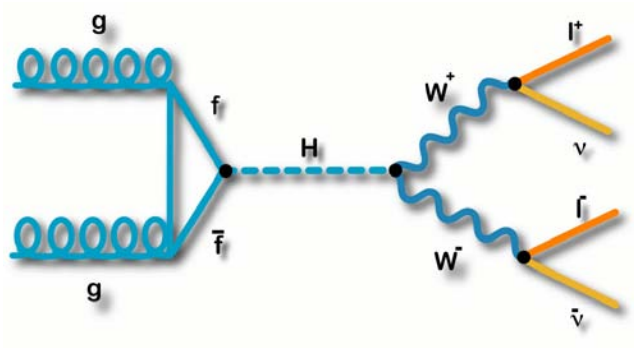
Charged leptons: $e^{\pm}$ $\mu^{\pm}$ $\tau^{\pm}$ or jets

Neutrinos: Missing Transverse Energy (MET)

and always b-quarks

Note: the above categories overlap
if a lepton is failed detection

The main final state for M_H > 135 GeV (gluon fusion)

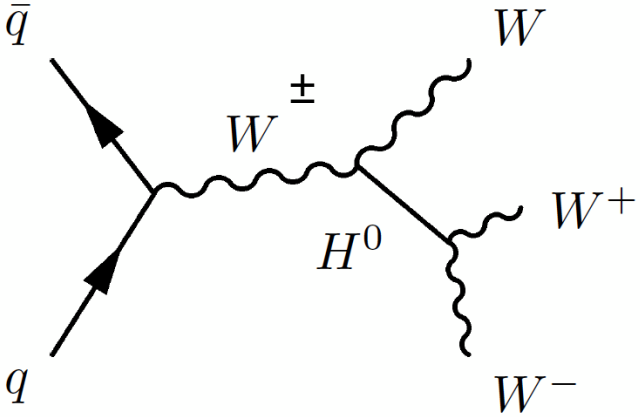


Opposite sign (OS) charged leptons and MET

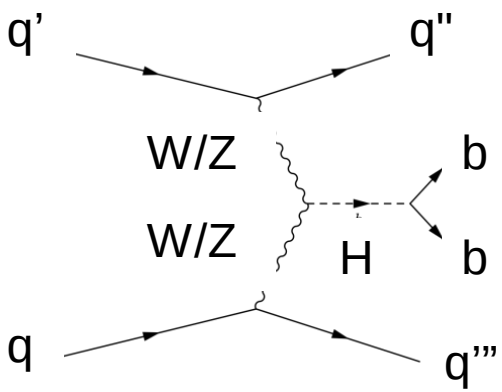
Also considered:
charged lepton + MET + jet-pair

Enhanced if >3 generations exist

At intermediate masses:
Higgs Strahlung + H→W W → $W^{\pm}$ ($W^{\pm}$ $W^{\mp}$) → $l^{\pm}$($l^{\pm}$ jj or$l^{\mp}$)
like sign lepton-pair + jets or trileptons are also considered



Other final states (production and decay mechanisms) also considered



Vector Boson (W/Z) Fusion (VBF)

$q_1q_2 \rightarrow (V^*V'^*)q_3q_4 \rightarrow Hq_3q_4$ (tagged by 2 jets)

~ 2 x smaller than Higgs Strahlung – still non negligible

Associate production with a top pair

$g \rightarrow t^*t \rightarrow Htt \rightarrow bbtt$

Small cross section – but contributes to the limits

Enhanced if g is replaced by massive $G' \rightarrow t't \rightarrow Htt$

$H \rightarrow \gamma\gamma$

Small BR in SM (~10^{-3}) – but contributes to the limits

since smaller QCD background and better mass resolution then $H \rightarrow bb$

Enhanced (~30 x) if H doesn't decay to fermions (fermiophobic Higgs)

$H \rightarrow \tau\tau$

Enhanced in MSSM by $\sim\tan^2\beta$

Main steps of the event selection and analyses

- Trigger
- Off-line object reconstruction/identification
- Event pre-selection
- Final selection: signal enhancement
- Estimation of the Higgs signal

Trigger

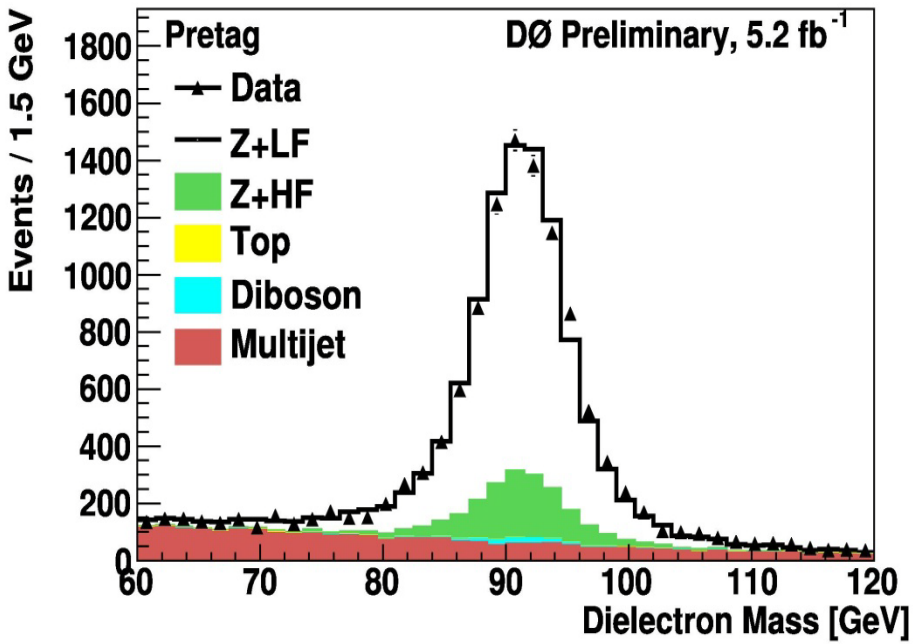
Primary trigger on high p_T e and μ (almost all channels have)
Jet+MET triggers: modes with no charged leptons (ex.: ZH→vvbb search)
Dedicated τ triggers

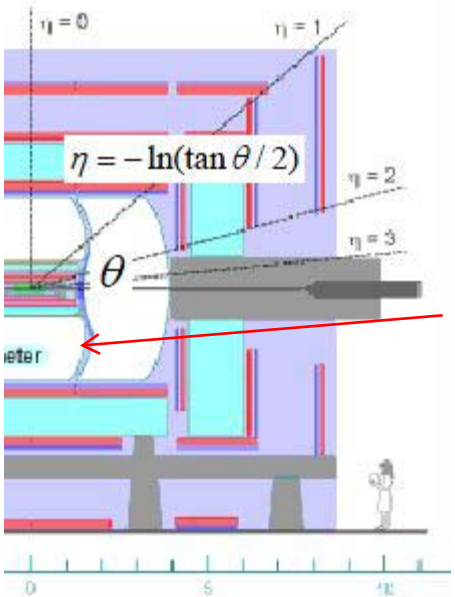
3-level decision

typical rates (D0) : 5-10 MHz interaction rate → ~2 kHz (L1)→ ~1 kHz (L2)→ ~200 Hz (L3)

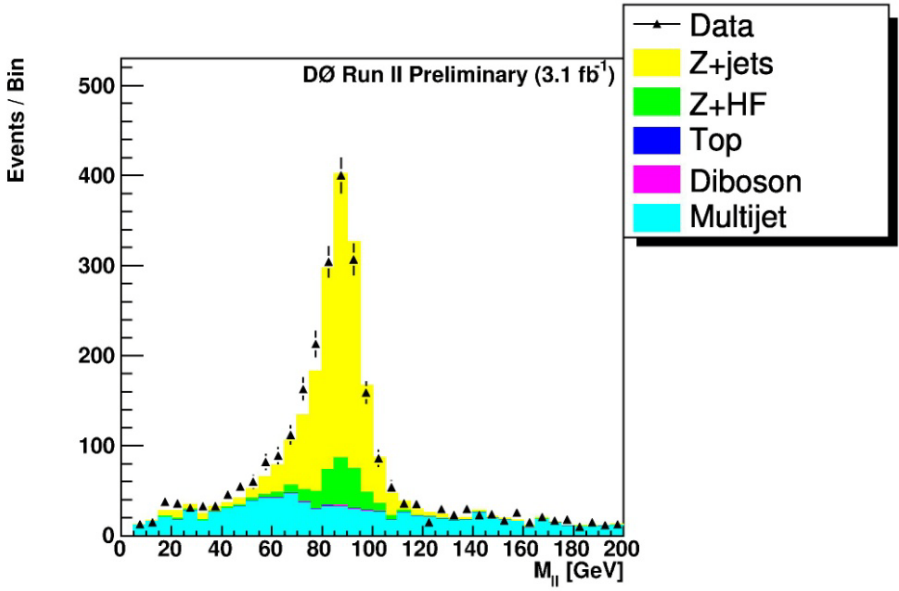
To be compared with the Higgs production rate (M_H=115 GeV) ~ 55/fb^{-1} = 3.5 10^{-6} Hz

Identification of the Z boson

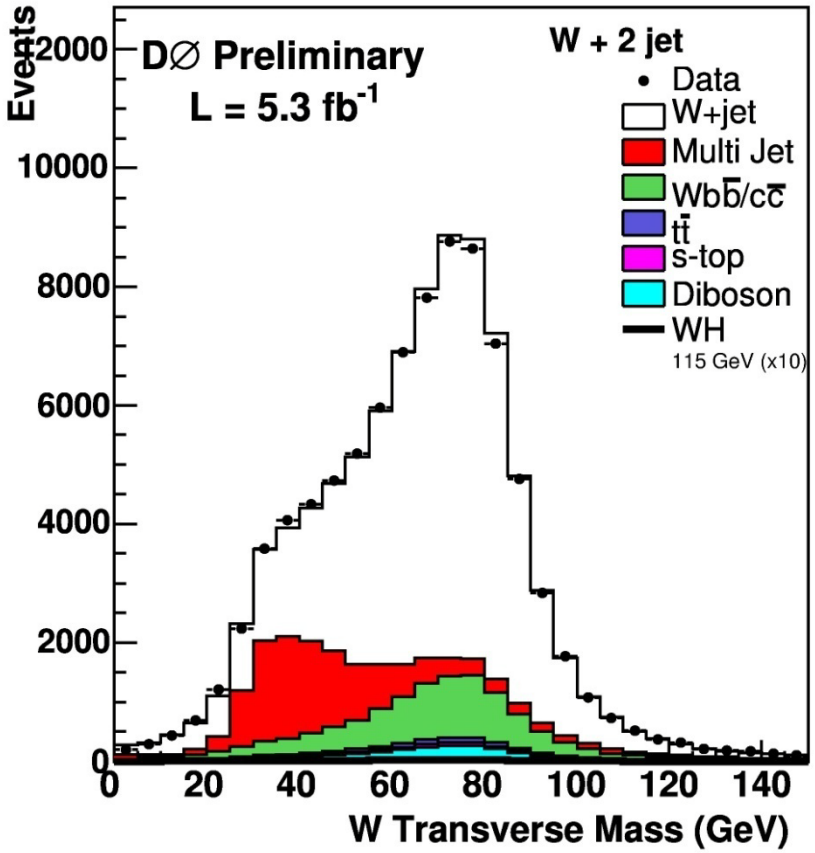




One of the electrons in the inter-cryostat region



Identification of the W boson



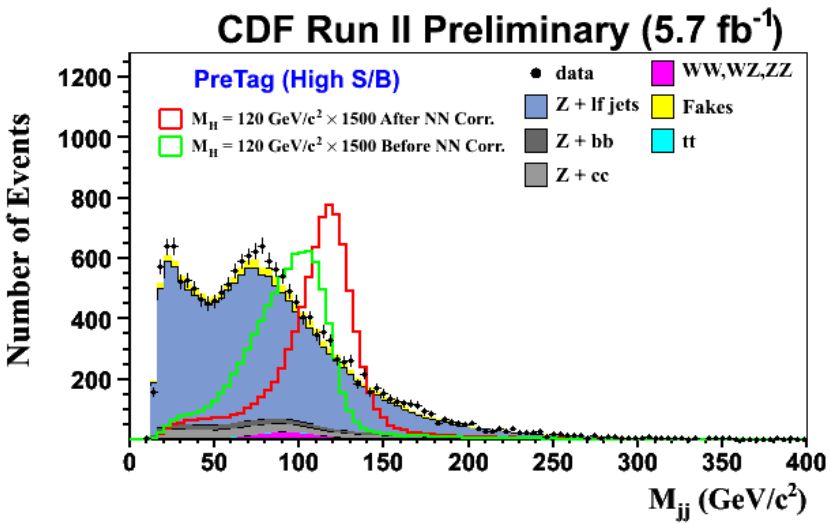
$M_{WT}(l\nu)$

W transverse mass in the WH→lνbb search after requirement of a lepton, MET and 2 jets

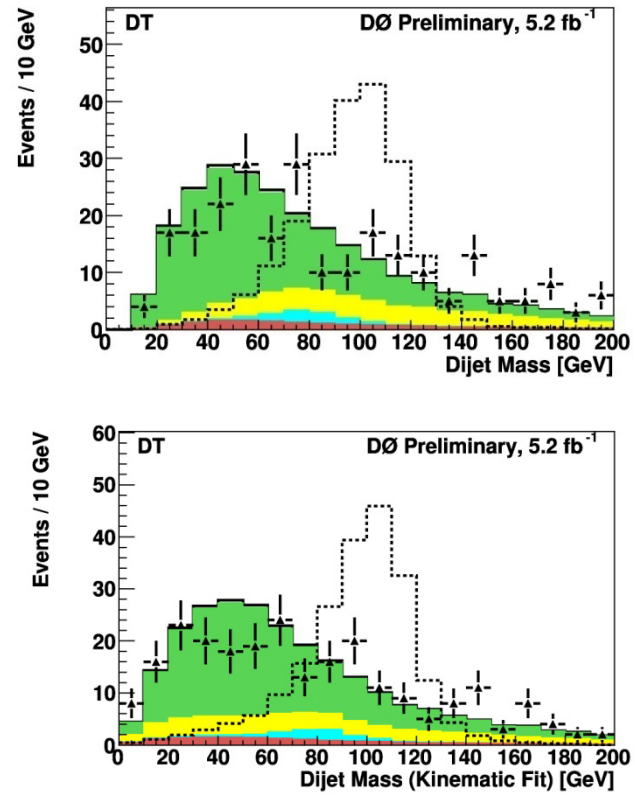
Jet energy scale and resolution (di-jet mass)

Constrained kinematic fits when no missing E_T is expected

Neural Network based jet energy corrections



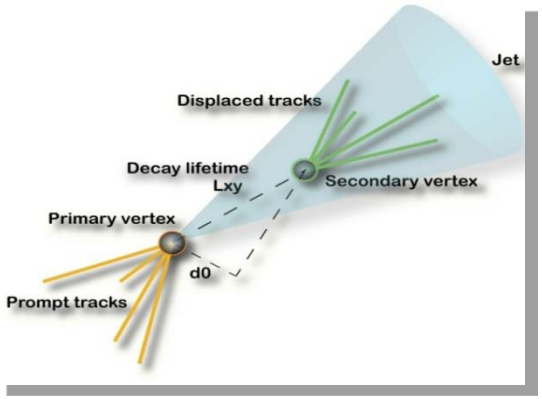
Dijet mass for pretag events in the ZH→llbb search showing the effect of NN jet energy corrections on signal

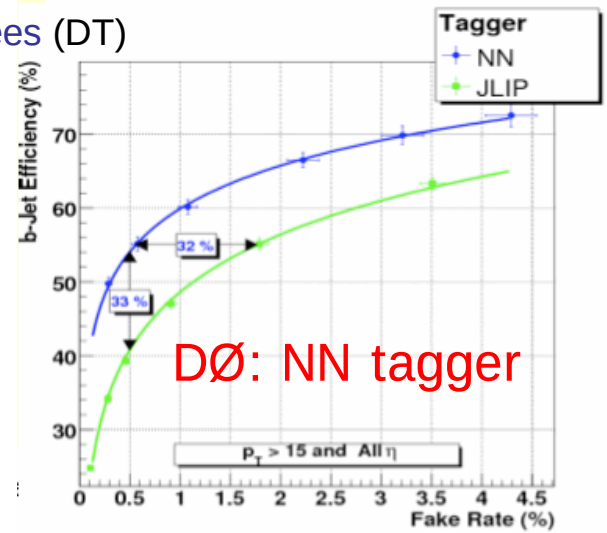


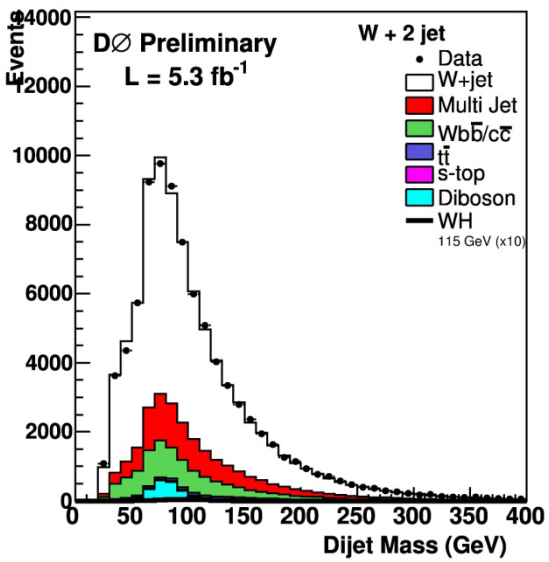
Di-bjet mass in the ZH→llbb search before (above) and after (below) the kinematic fit

b-tagging

Uses the fact that b-quarks has non-negligible finite life time
Search for secondary vertex
Calculate jet lifetime probability (JLIP) from impact parameters
Combine these information in a Neural Network (NN) or Decision Trees (DT)

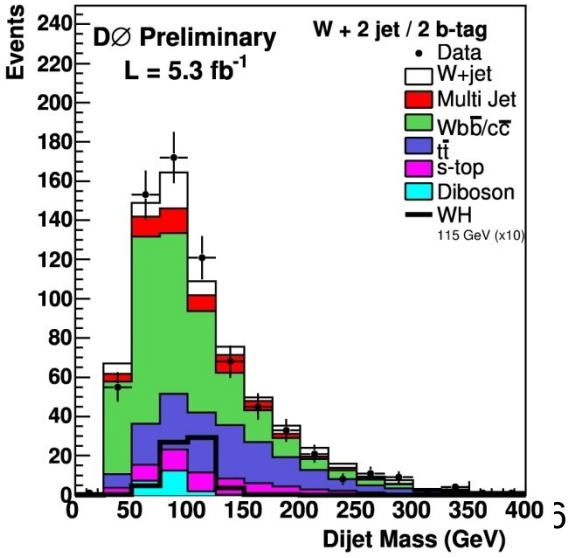






Di-jet mass spectrum in the WH→lνbb search before and after b-tag

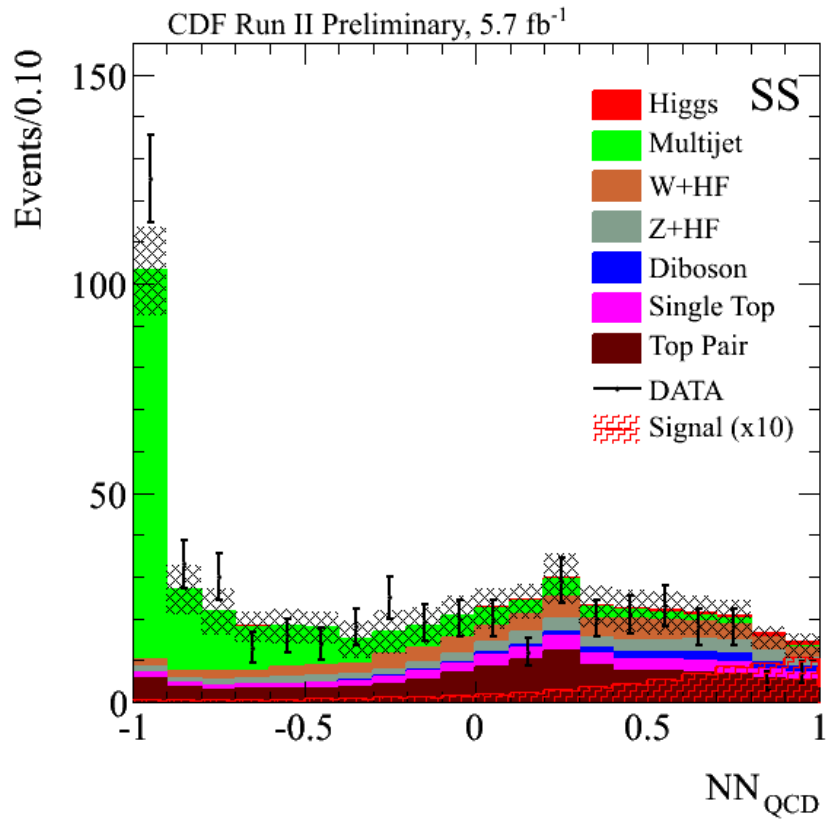
S/B ~ 1/3500 → S/B ~ 1/100



Off-line Event Preselection

- Demonstrate the good understanding of the detector
  In a signal depleted region compare data with the SM background
  EW backgrounds (W/Z+jets, W/Z+HF, ttbar→bbllvv, single-top, di-boson,…)
  simulated by MC with NLO (NNLO) cross sections
  Multijet (instrumental) background determined from data
  mismeasured energy, leptons faked by jets,…
- Select the region enhanced by the signal

NN output to separate the signal from the multijet background in the ZH→vvbb search.

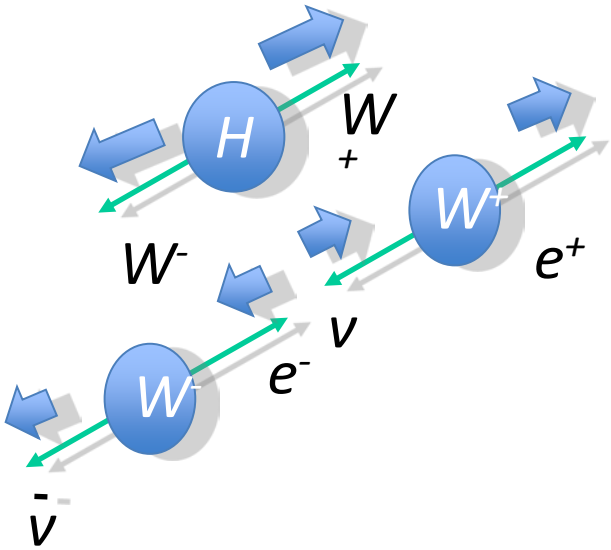


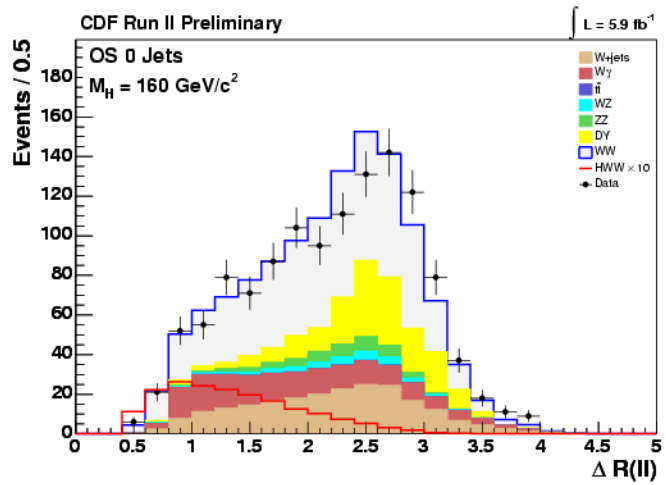
Final event selection

to search for siginificant difference between the data and the background which is compatible with the Higgs signal

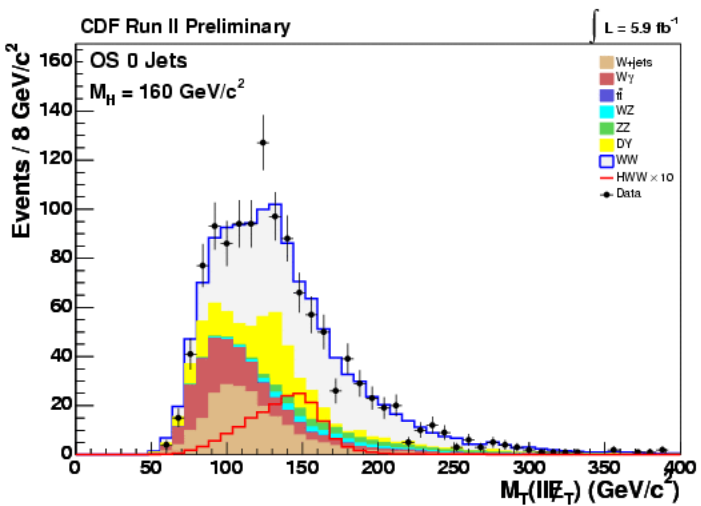
using multivariate analysis (MVA) techniques

- Likelihood discriminants (e.g. based on ME of the signal and background)
- Neural Network
- Boosted decision tree,…

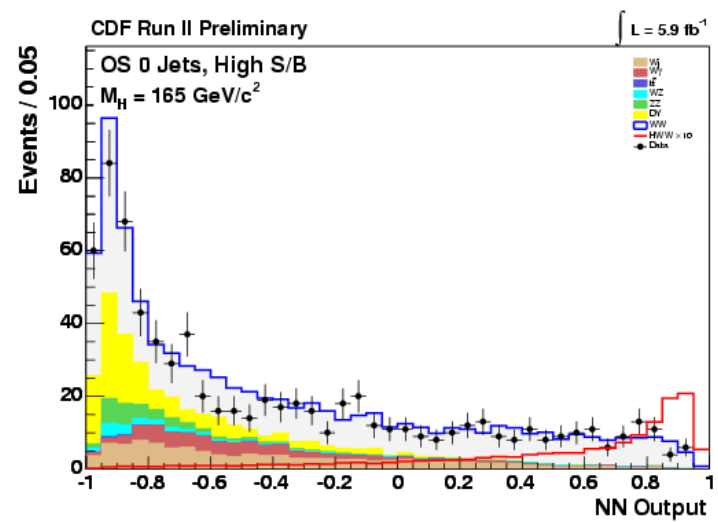




The directions of the charged leptons tend to align from the decay of a spin 0 particle



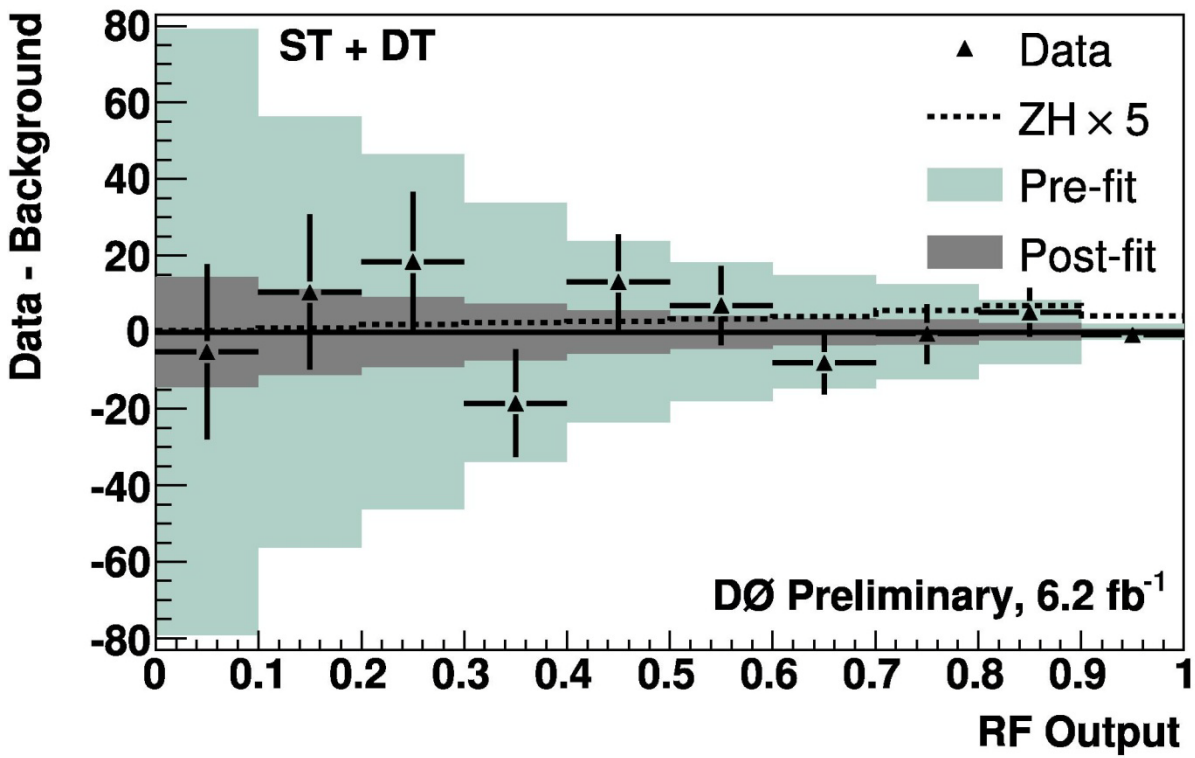
Examples of inputs and the output NN in the search of the gg→H→WW→eeνν



Systematic uncertainties

- p-pbar cross section used in luminosity calculation 3.8%
- Luminosity measurement 4.5%
- Signal and background cross sections used including (HF) k-factors, PDF's 6-30%
- Object reconstruction and identification efficiencies (leptons, jets, b-tagging) 1-10%
- Energy scale calibration ~7%
- …

Some of them are correlated between experiments/channels/bins affecting normalization but also shapes of distributions



Background subtracted data distribution of the final discriminant in the ZH→llbb analysis.
The background has been fitted to the data within its systematic uncertainties (light blue area).
The systematic error after the fit is also shown (grey area)

No significant signal excess was found beyond the expected background in any of the 20 analyzed channels

Setting upper limit on the Higgs production cross section @ 95% CL

Use binned Poissonian likelihoods on final MVA distributions

systematic errors with correlations are taken into account in the limit

CDF: Bayesian posterior probability (by integrating over nuisance parameters)

D0: CLs method (ratio of confidence levels of s+b and b-only LLR distributions with fitting nuisance parameters to data)

Expected limits are calculated using background-only pseudo-experiments

The two methods give compatible results

Upper limits are expressed in units of the SM Higgs cross section: R

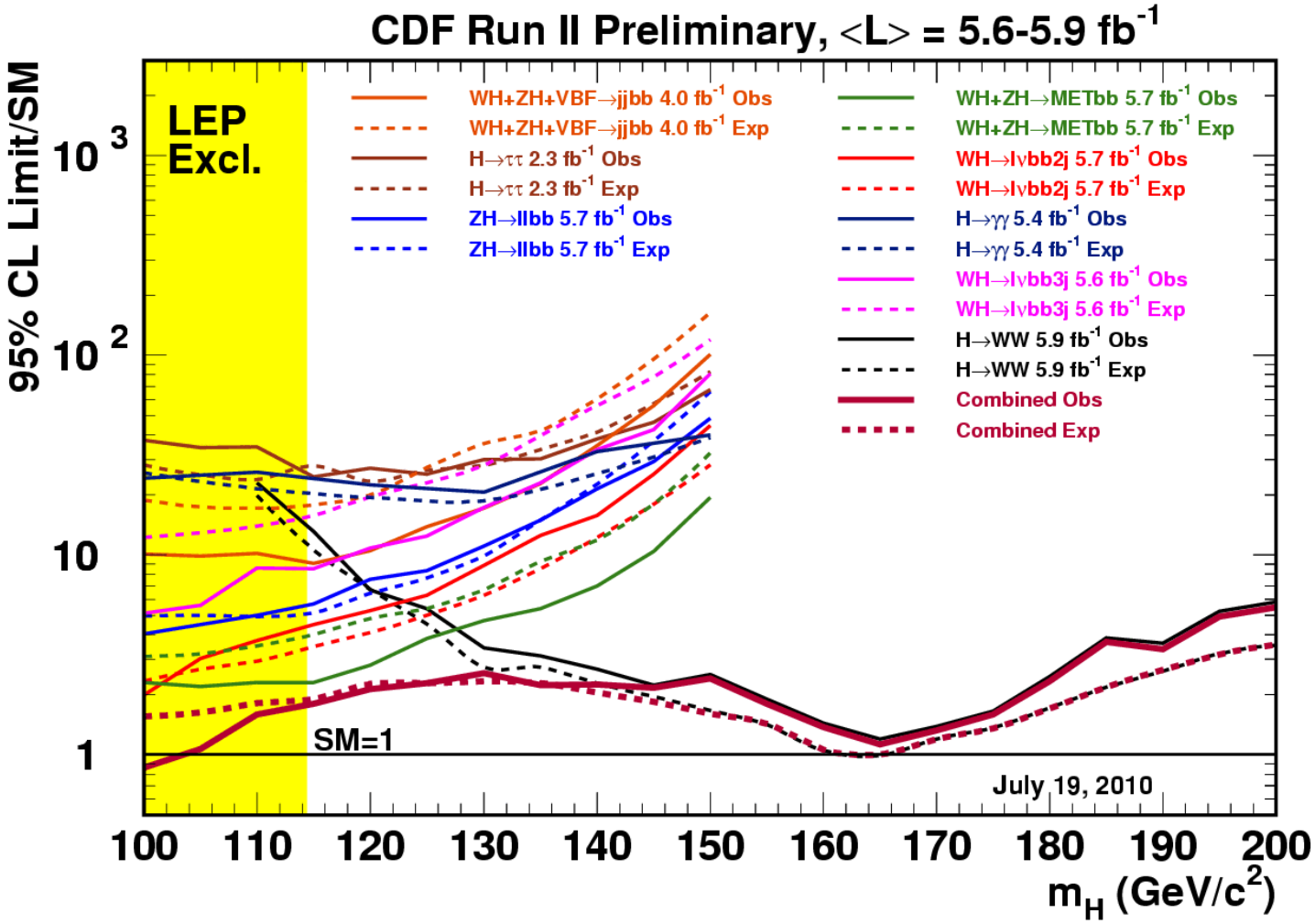
calculated at NNLO in QCD with NNLL soft gluon resummation

includes 2-loop EW effects

running b quark mass

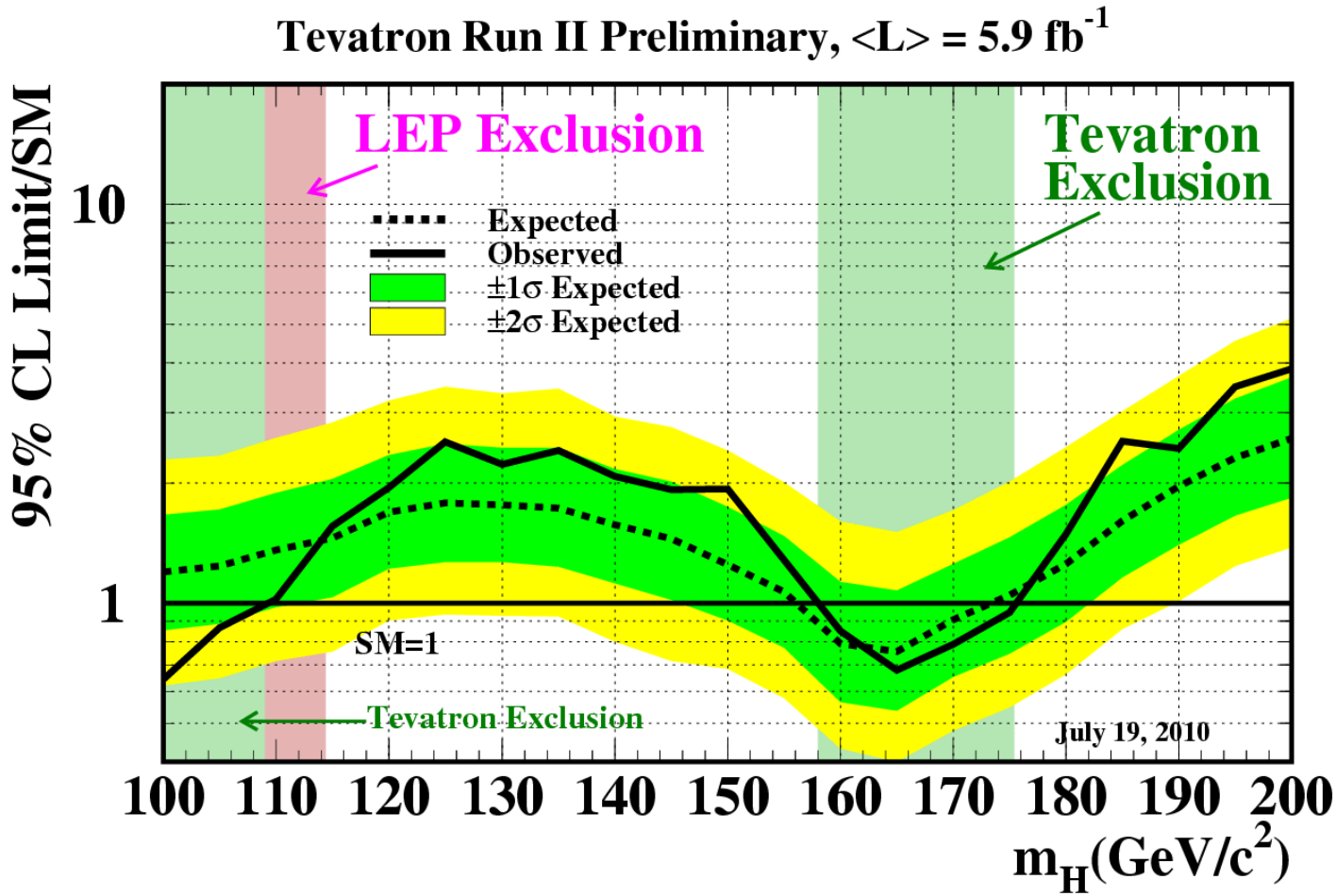
For R < 1: Higgs production is excluded by 95% CL

Overview of the channels studied at CDF



Both CDF and D0 combines their proper channels, and produce also an overall combination by selecting non-overlapping (orthogonal) datasets

Most recent Tevatron combination



Bayesian σ/σ_{SM} limits @ 95% CL

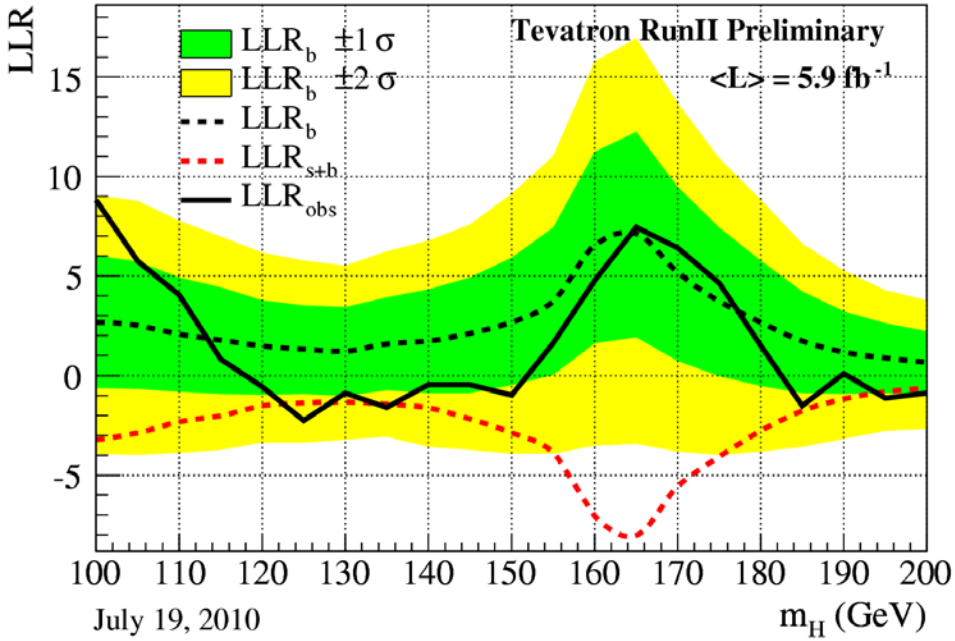
M_H(GeV)	115	160	165	170
Expected	1.45	0.79	0.76	0.91
Observed	1.56	0.85	0.68	0.79

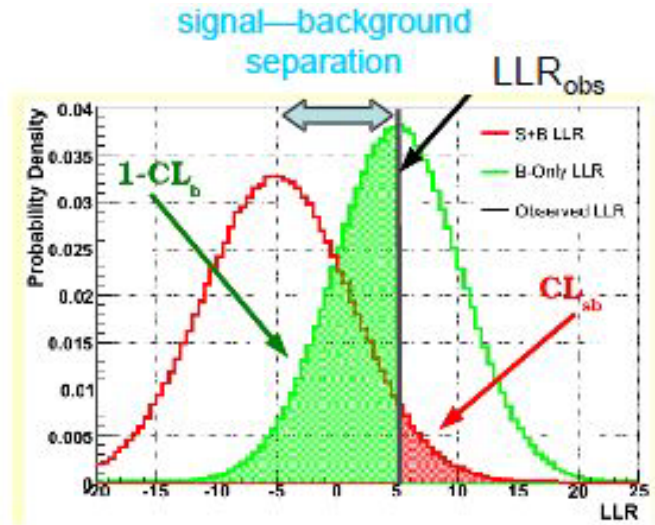
The mass range of $158 < M_H < 175$ GeV excluded at 95% CL

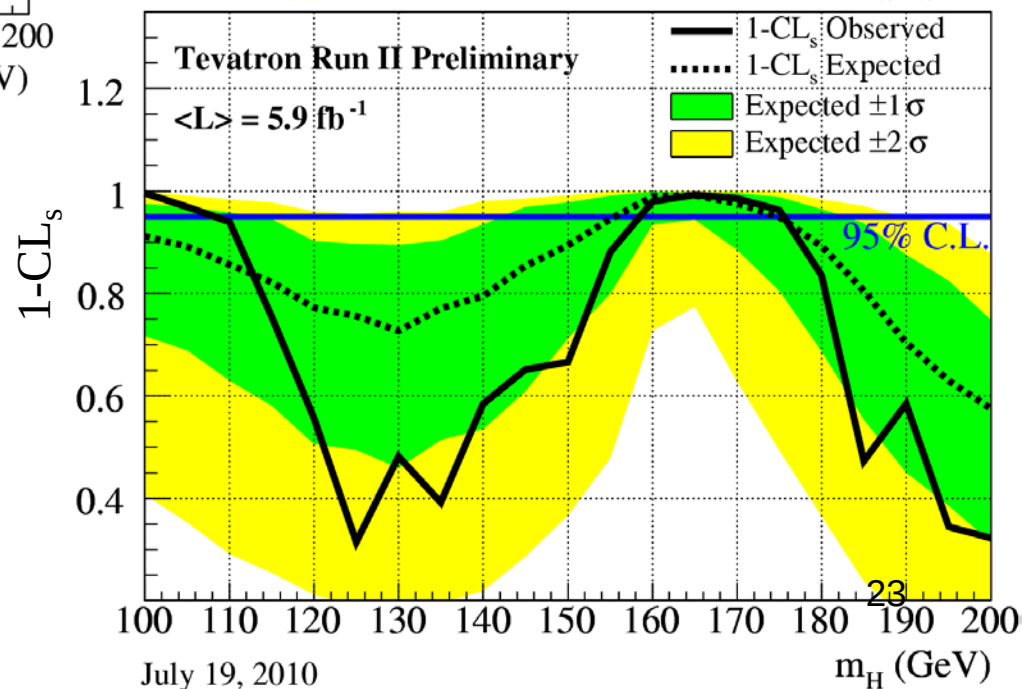
Most recent Tevatron combination

CL_s method

$$LLR = -2\ln\frac{P(N|H_1)}{P(N|H_0)}$$







Confidence levels:

$1\text{-}CL_b = p(LLR_b < LLR_{obs}|H_0)$

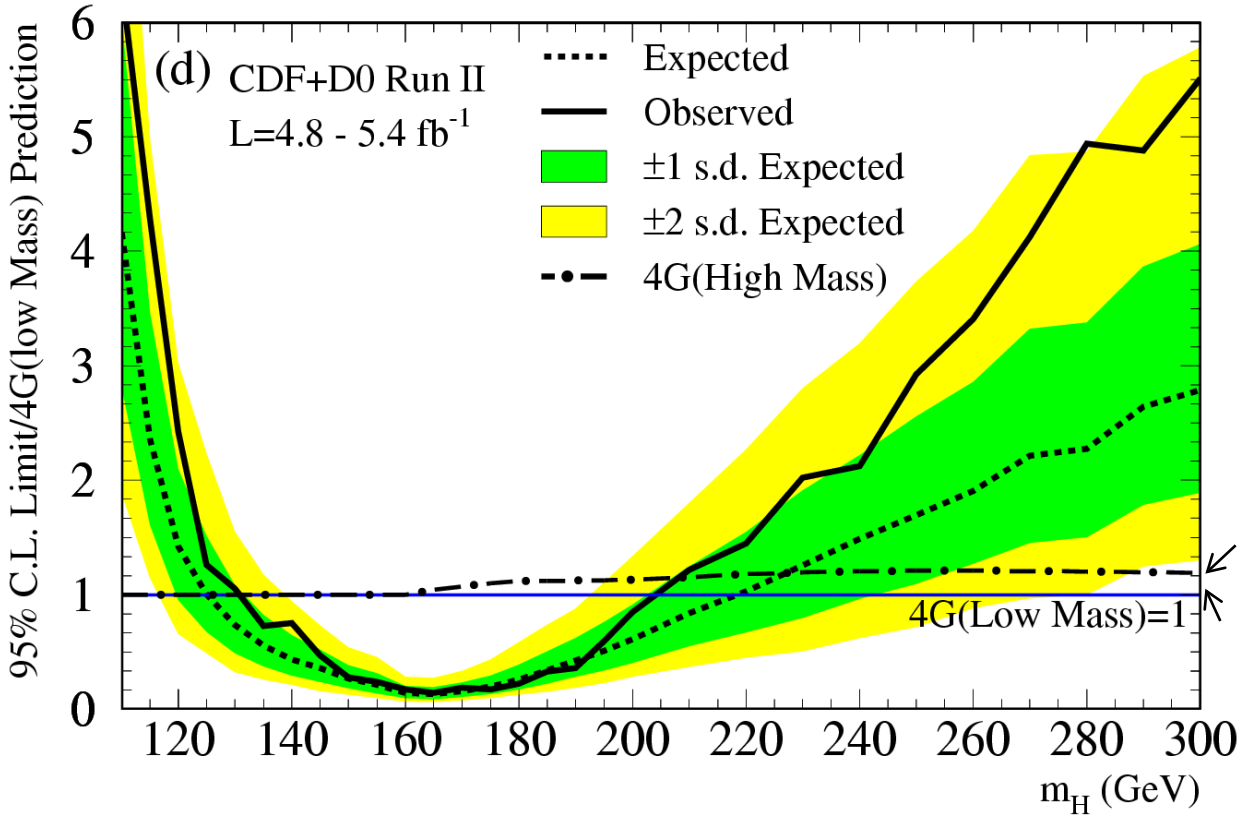
$CL_{sb} = p(LLR_{sb} > LLR_{obs}|H_1)$

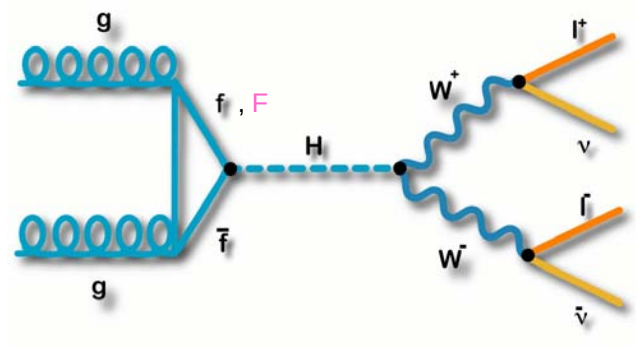
$CL_s = CL_{sb}/CL_b$

BSM Higgs Search

4th generation Higgs limit

H→WW* is sensitive to > 3 SM generation since
- additional heavy fermion (F) loops in the dominant gg-fusion process enhances ~9 times the Higgs production cross section
- the WW* decay is the best suited to study the gg-fusion production the bb and gg final states are swamped by the QCD background





$M_{l4}=M_{\nu4}$=1TeV (High Mass)

M_{l4}=100 GeV $M_{\nu4}$=80GeV (Low Mass)

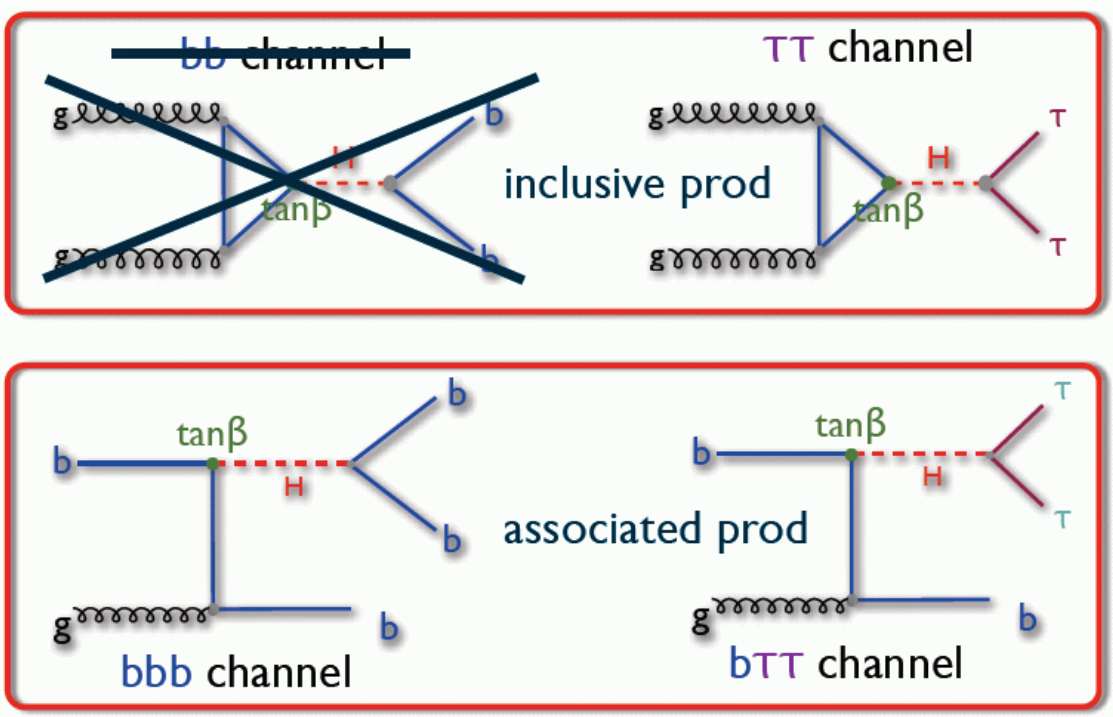
SUSY Higgs

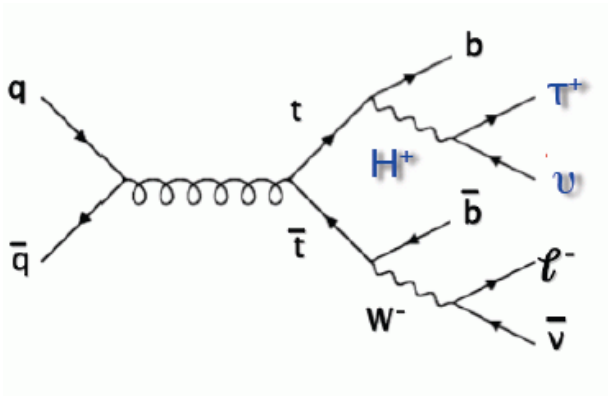
2 complex Higgs doublet → 5 Higgs particles: h, H, A, H^+, H^-

At tree level the MSSM is fixed by 2 parameters: $\tan\beta = v_u/v_d$, M_A
Other parameters enter via radiative corrections
Predictions:
- $M_h < 135$ GeV
- Couplings to d-type fermions ~ tanβ → search is advantageous at high tanβ
- At high tanβ h/A or H/A are degenerate (Φ) → $\sigma_{prod} \times 2$

For neutral Higgses: most sensitive final states are bbb, bττ or ττ

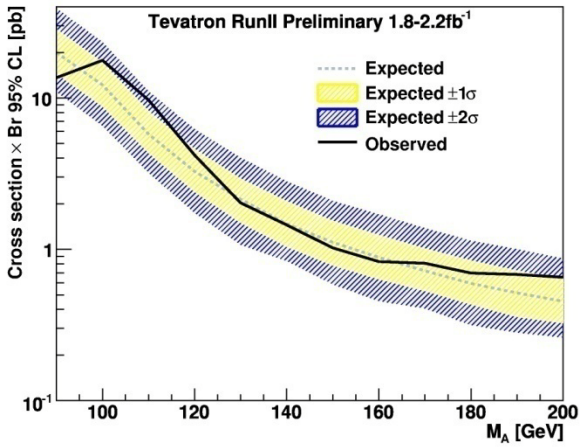
For charged Higgses: $M_{H+} < M_t$

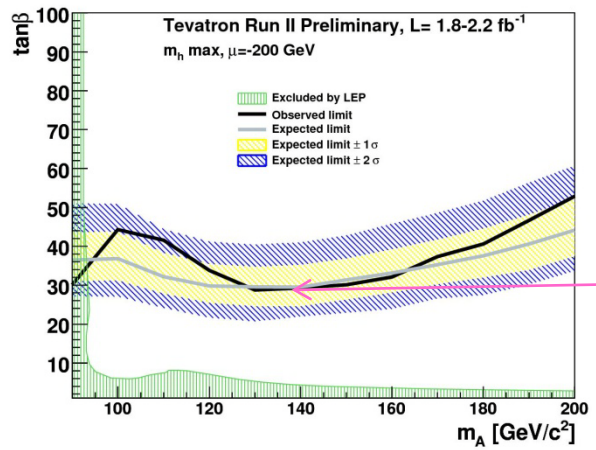




Assuming $B(H^+ \to \tau\nu) = 1$

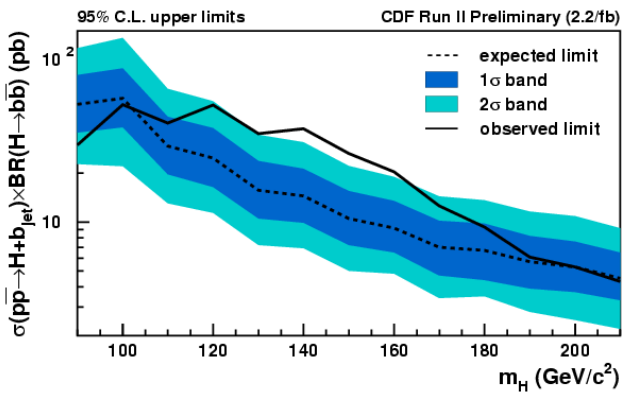
Tevatron combination of the $\Phi \rightarrow \tau\tau$ search

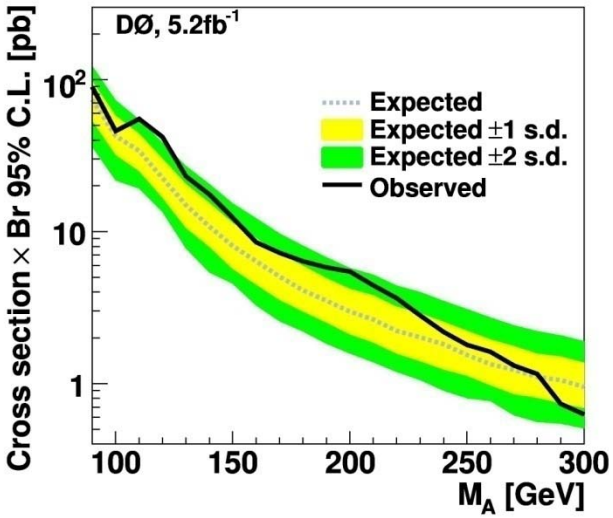


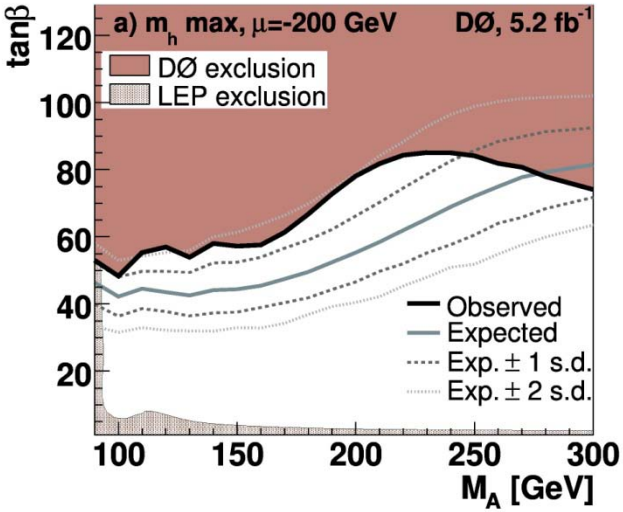


M_t/M_b

Recent results of the search for 3b-tagged final states

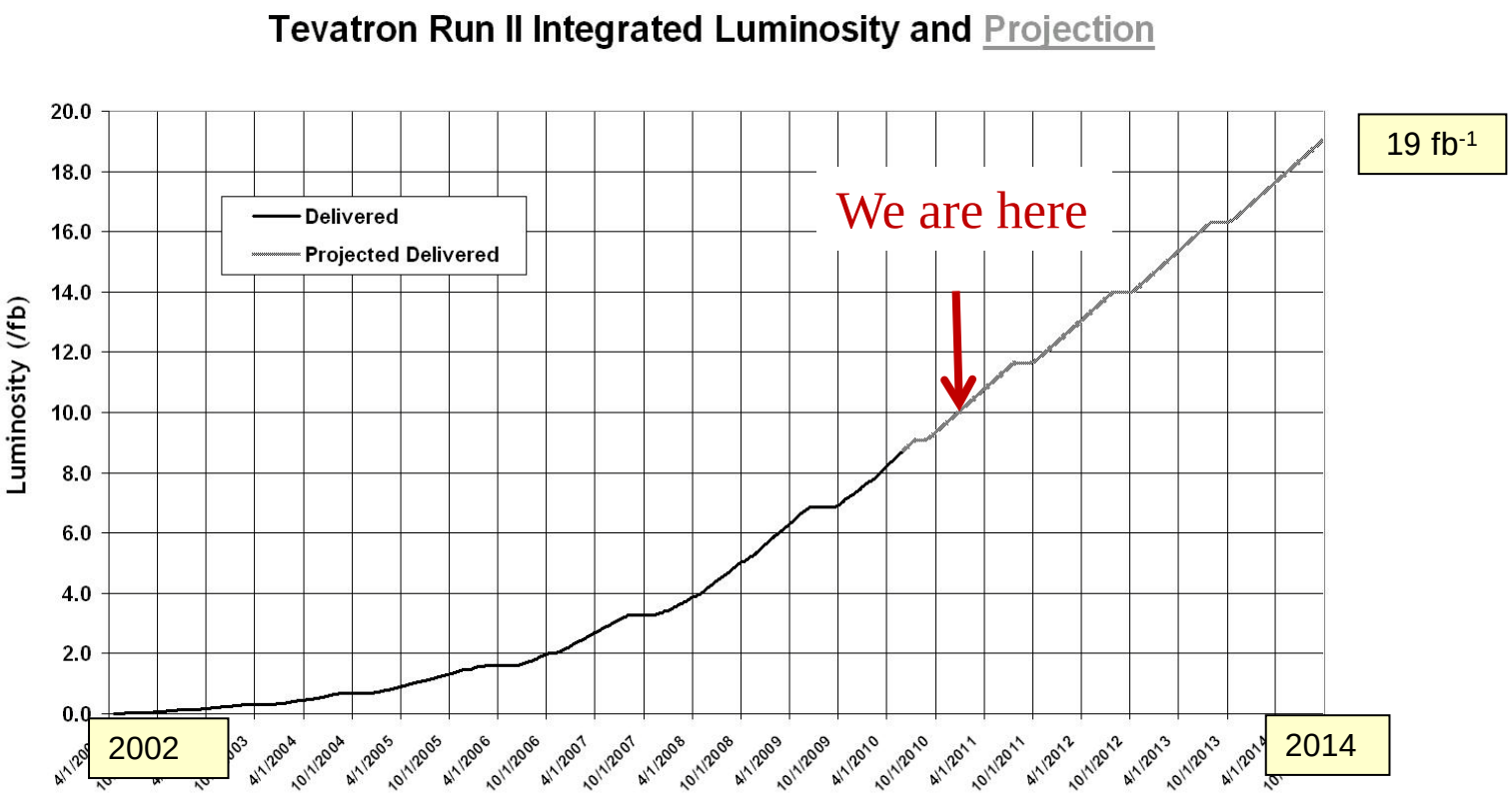






Miami 2010 Dec 16

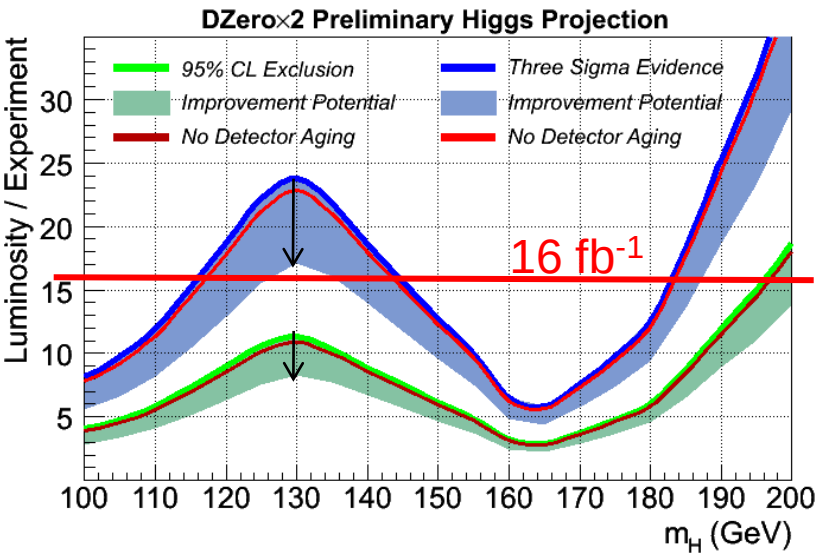
Perspectives of the Higgs searches at the Tevatron

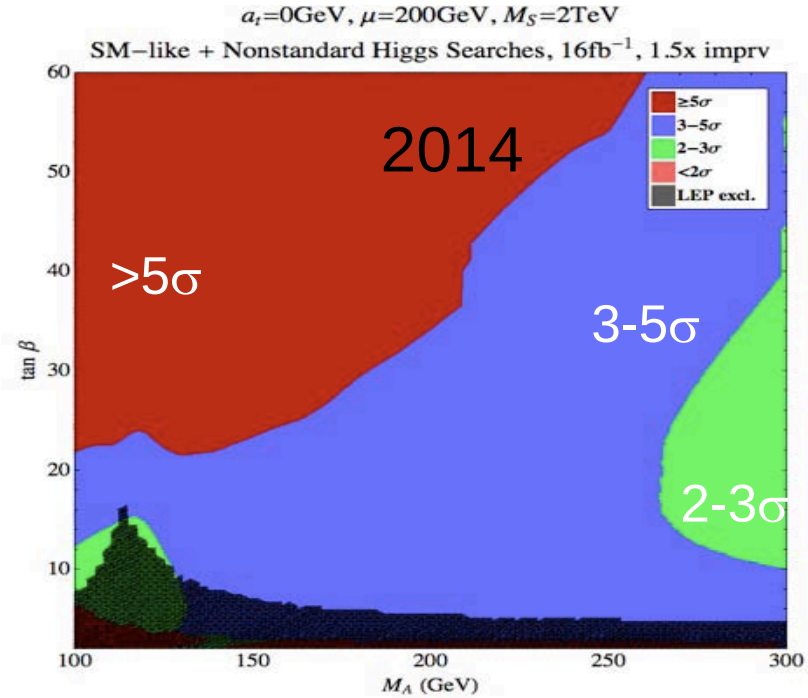


Strong recommendation from HEPAP for three more years running of the Tevatron:
Provides doubling of the current data set: ~16 fb^{-1} for analyses
Tevatron luminosity plan is demanding, but achievable
Some degradation of the detectors can be compensated with new algorithms

Projected expected limits including improvements

Add new channels
Increase acceptance
Increase efficiencies using looser event selection
Better object identification (leptons, jets, b, c, τ)
using MVA
Better signal/background separation
using MVA
Improve di-jet mass resolution
Improvement in signal and background simulation
theory: higher order corrections
experiment: better parameterization of detector effects (resolution, etc.)
Experimental determination of different background processes (e.g. Z+b)
…..





- By 2014 one can expect 3σ evidence for M_H<185 GeV or exclude the SM Higgs upto M_H < 200 GeV
- Possibility to exclude MSSM Higgs with M_A<300 GeV

Summary

Most recent, preliminary results on Higgs searches at the Tevatron were shown obtained by the CDF and D0 collaborations using upto 6.7 fb^{-1} integrated luminosity.
The mass region of $158 < M_H < 175$ GeV has been excluded.
Sensitivity at lower masses will reach soon the SM prediction.
Thanks to the excellent performance of the Tevatron,
efficient and well understood detectors
constantly improving and innovating analysis techniques
one will be able to exclude the Higgs in 2011 upto $M_H < 195$ GeV at 95% CL,
and one expects 3σ evidence by 2014 upto $M_H < 185$ GeV.

The Tevatron remains in the race for finding the Higgs!

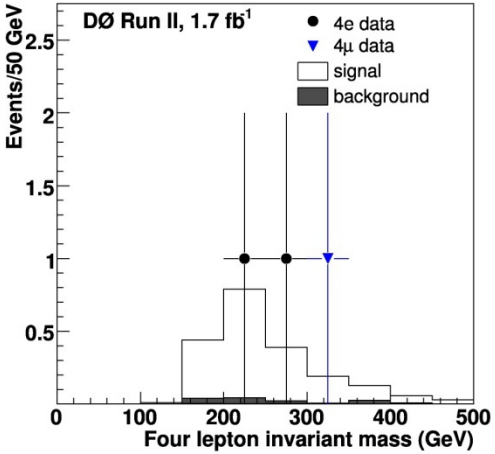
More details can be obtained from the CDF and D0 web pages
http://www-cdf.fnal.gov/physics/new/hdg/Results.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

Backup slides

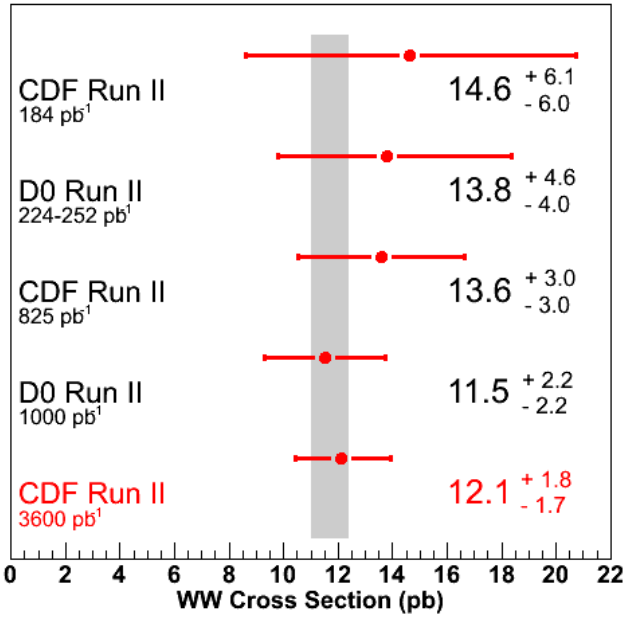
Status of the di-boson (WW/WZ/ZZ) search at the Tevatron

Channel	D0		CDF	
ZZ→llll	1.7 fb^{-1}	5.3 sd		
ZZ→llvv	2.7 fb^{-1}	2.6 sd		
ZZ→4l comb	1.7+2.7fb^{-1}	5.7 sd		
WZ→lvll	4.1fb^{-1}	4.5 sd		
WZ→lvqq	1.1 fb^{-1}	4.4 sd	4.6 fb^{-1}	5.4 sd
WZ/ZZ→lvbb			5.5 fb^{-1} Upper limit	
WW→lvl'v'	1.1 fb^{-1} 11.5+/-2.5		3.6 fb^{-1} 12.1+/-2 pb	

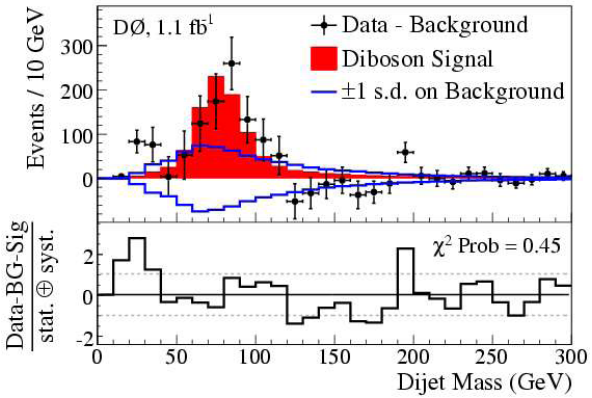
ZZ→llll

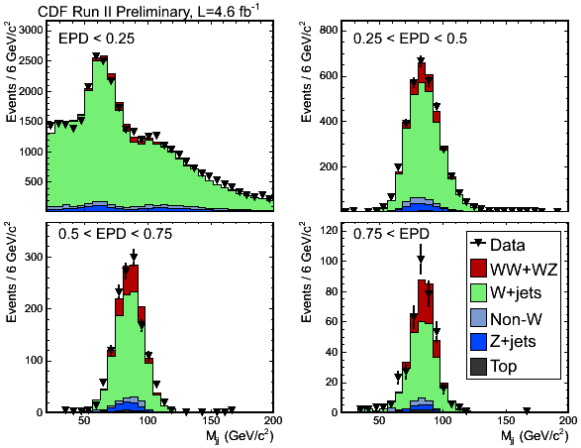


WW→lvl'v'

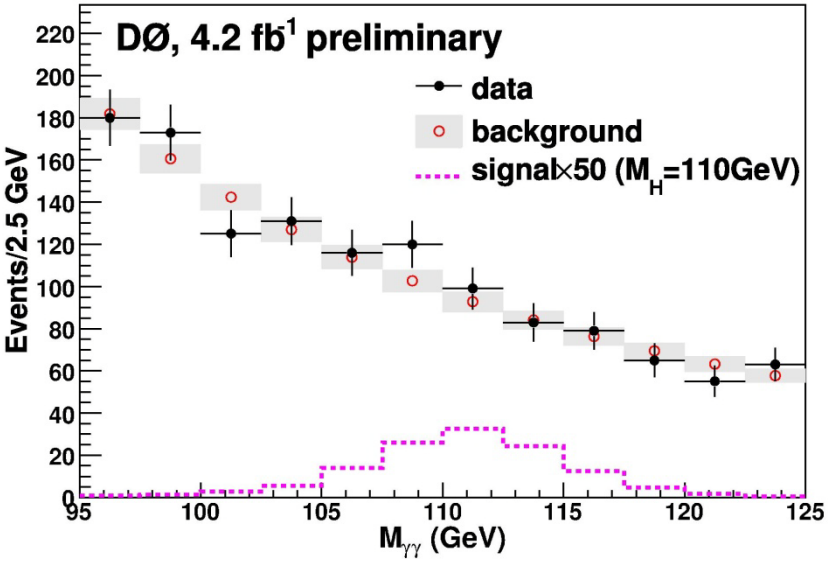


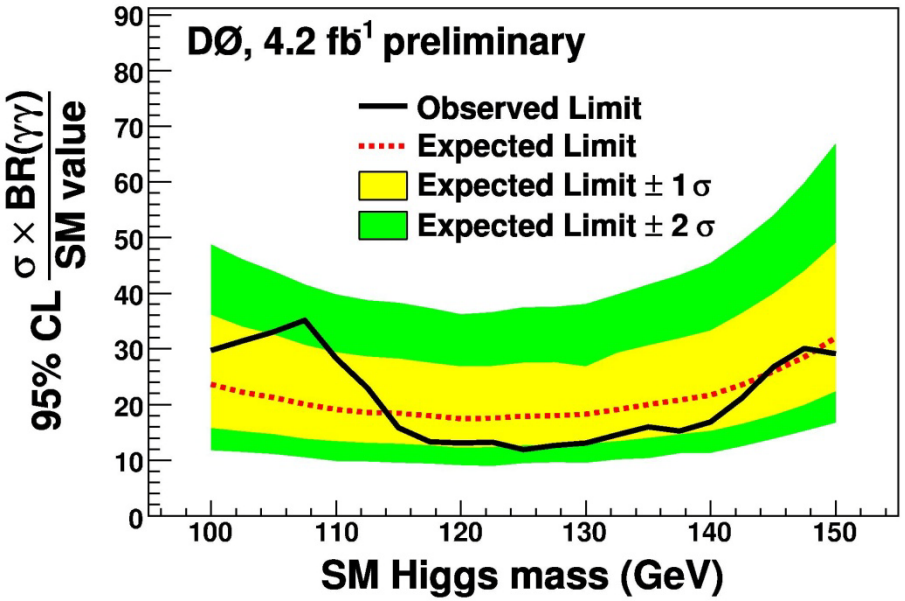
WW/WZ→lvjj





H→γγ search

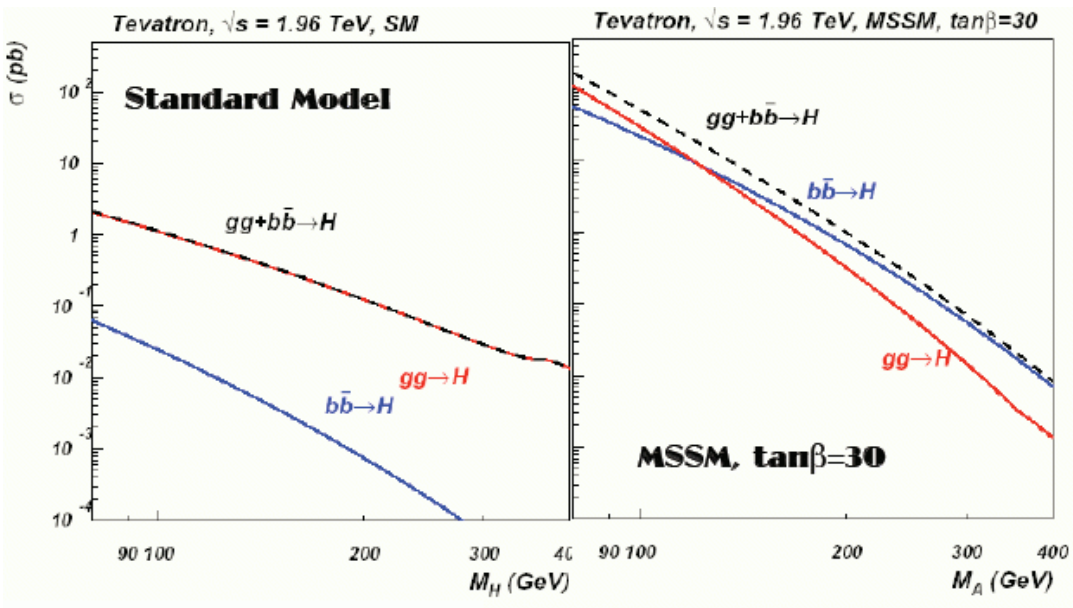

DØ, 4.2 fb-1 preliminary
data
background
signal×50 (MH=110GeV)
Events/2.5 GeV
Mγγ (GeV)

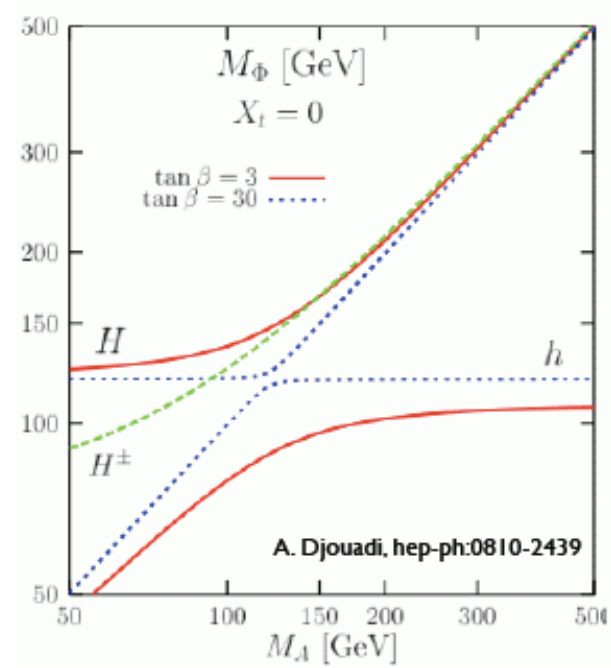

DØ, 4.2 fb-1 preliminary
Observed Limit
Expected Limit
Expected Limit ± 1 σ
Expected Limit ± 2 σ
95% CL σ × BR(γγ) / SM value
SM Higgs mass (GeV)

SUSY Higgs

2 complex Higgs doublet → 5 Higgs particles: h, H, A, H^+, H^-

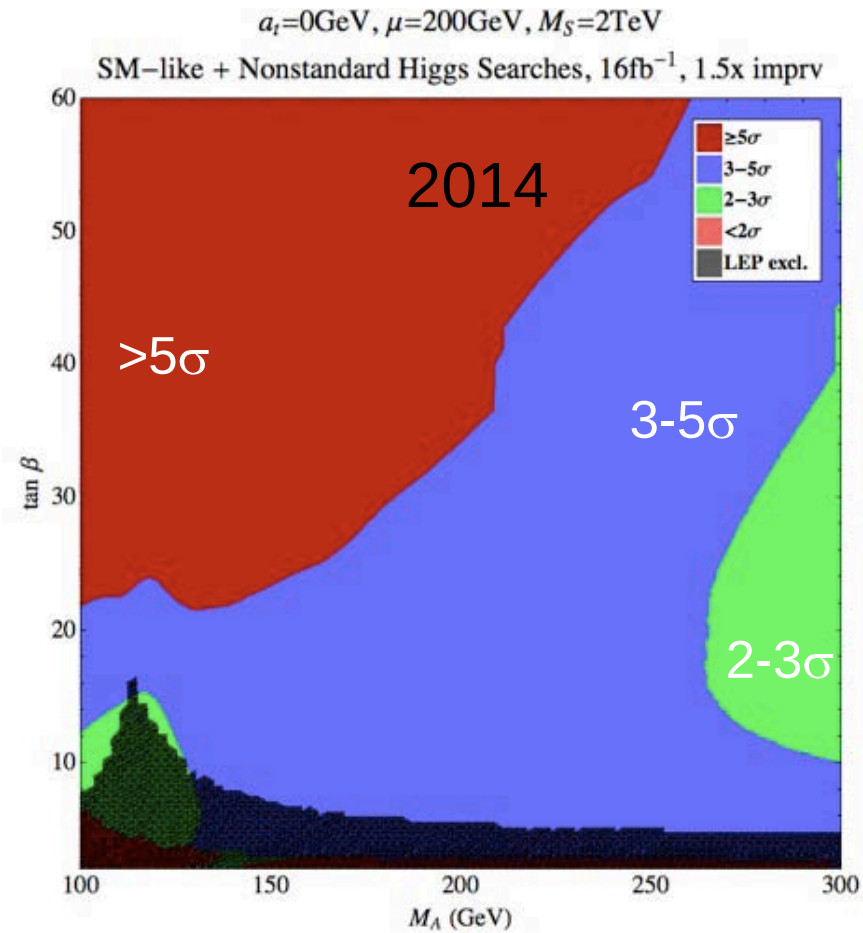
At tree level the MSSM is fixed by 2 parameters: $\tan\beta = v_u/v_d$, M_A
Other parameters enter via radiative corrections
Predictions:
- $M_h < 135$ GeV
- Cross sections are enhanced by $\tan^2\beta$ → search is advantageous at high $\tan\beta$
- At high $\tan\beta$ h/A or H/A are degenerate → $\sigma_{prod} \times 2$



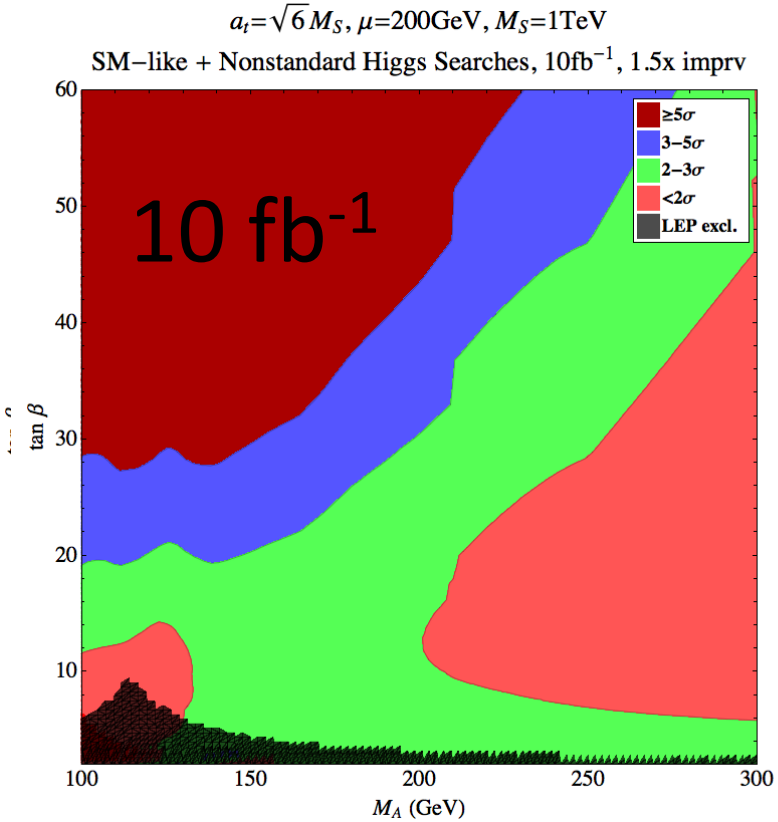


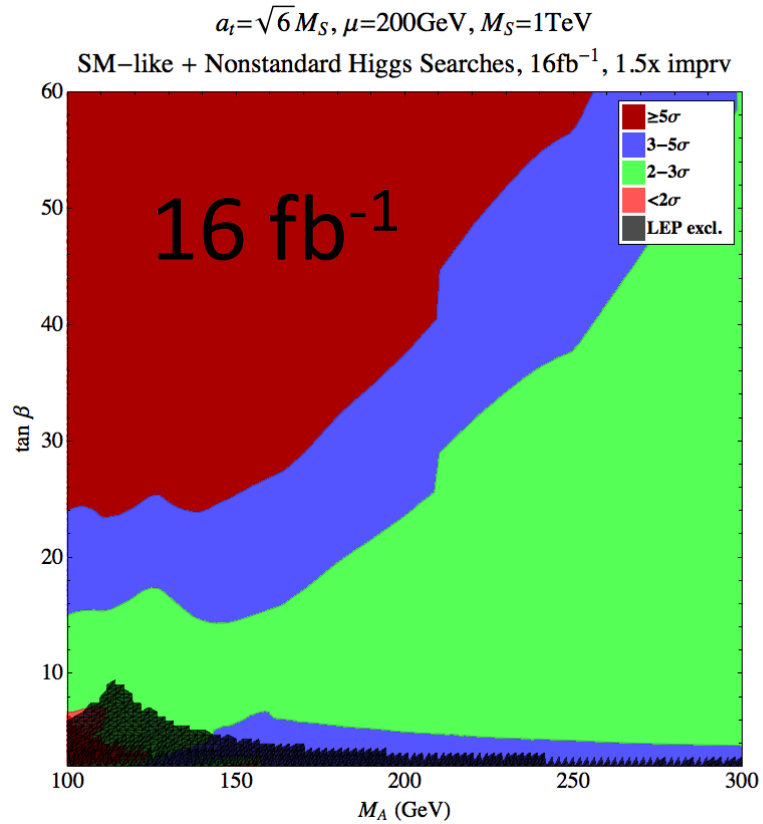
Phys. Rev. D 80, 035025 (2009)

Minimal mixing scenario ($m_h^{SM\text{-}like}$<120 GeV)



Example: Maximal Mixing Scenario

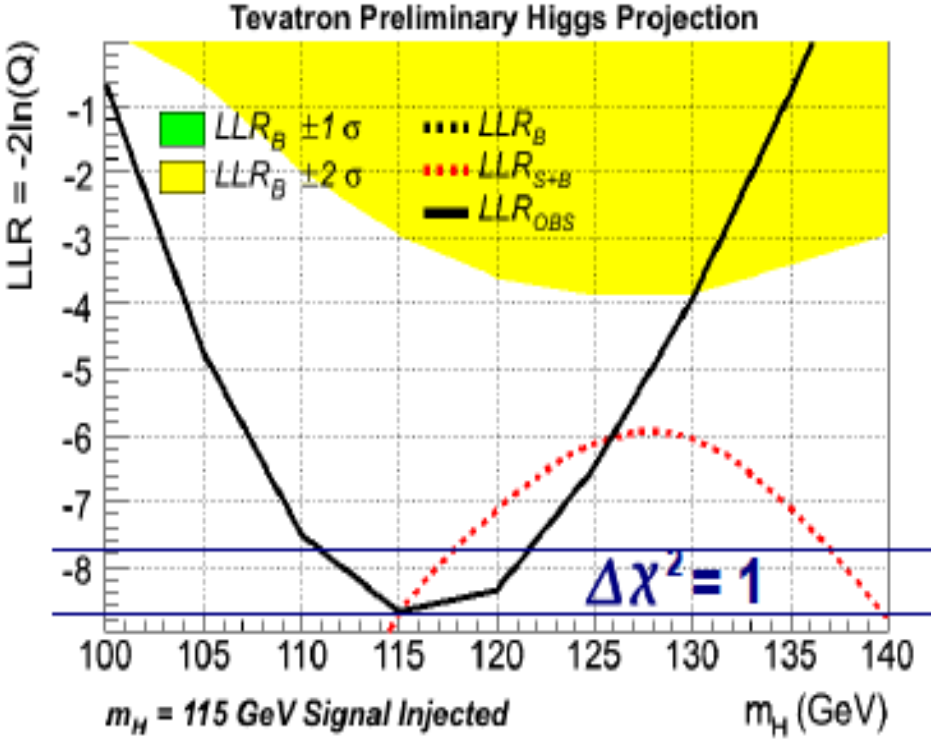




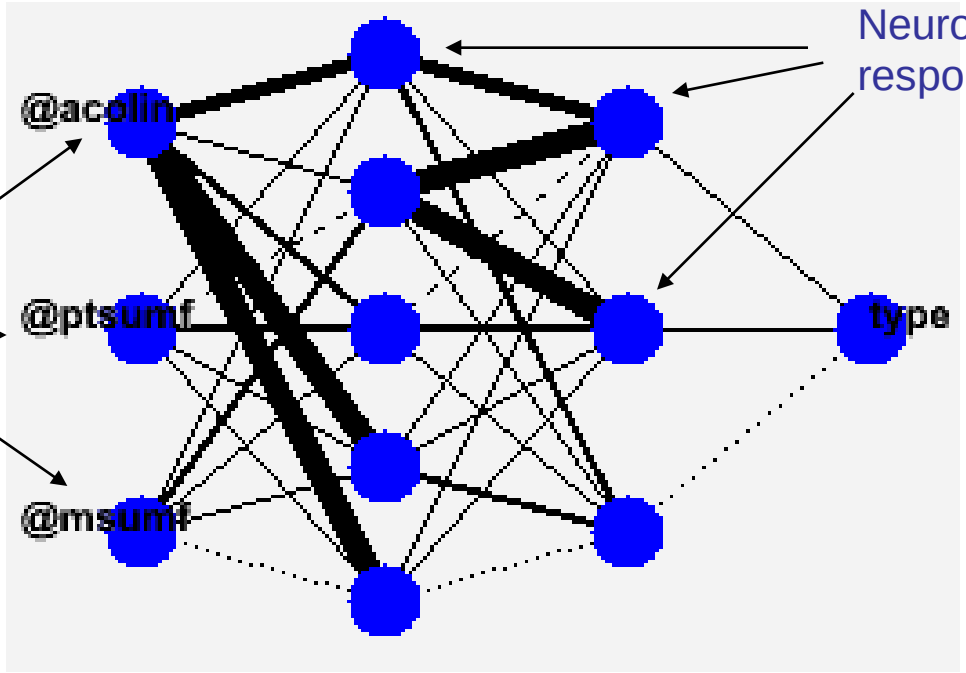
SM Higgs production cross section and decay BR's

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to \tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to \gamma\gamma)$ (%)
100	1861	291.9	169.8	99.5	80.33	3.542	7.920	1.052	0.1071	0.1505
105	1618	248.4	145.9	93.3	78.57	3.463	7.821	2.307	0.2035	0.1689
110	1413	212.0	125.7	87.1	75.90	3.343	7.622	4.585	0.4160	0.1870
115	1240	181.9	108.9	79.07	71.95	3.169	7.288	8.268	0.8298	0.2029
120	1093	156.4	94.4	71.65	66.49	2.927	6.789	13.64	1.527	0.2148
125	967	135.1	82.3	67.37	59.48	2.617	6.120	20.78	2.549	0.2204
130	858	116.9	71.9	62.5	51.18	2.252	5.305	29.43	3.858	0.2182
135	764	101.5	63.0	57.65	42.15	1.854	4.400	39.10	5.319	0.2077
140	682	88.3	55.3	52.59	33.04	1.453	3.472	49.16	6.715	0.1897
145	611	77.0	48.7	49.15	24.45	1.075	2.585	59.15	7.771	0.1653
150	548	67.3	42.9	45.67	16.71	0.7345	1.778	68.91	8.143	0.1357
155	492	58.9	37.9	42.19	9.88	0.4341	1.057	78.92	7.297	0.09997
160	439	50.8	33.1	38.59	3.74	0.1646	0.403	90.48	4.185	0.05365
165	389	44.6	30.0	36.09	1.29	0.05667	0.140	95.91	2.216	0.02330
170	349	40.2	26.6	33.58	0.854	0.03753	0.093	96.39	2.351	0.01598
175	314	35.6	23.7	31.11	0.663	0.02910	0.073	95.81	3.204	0.01236
180	283	31.4	21.1	28.57	0.535	0.02349	0.059	93.25	5.937	0.01024
185	255	28.2	18.9	26.81	0.415	0.01823	0.046	84.50	14.86	0.008128
190	231	25.1	17.0	24.88	0.340	0.01490	0.038	78.70	20.77	0.006774
195	210	22.4	15.3	23	0.292	0.01281	0.033	75.88	23.66	0.005919
200	192	20.0	13.7	21.19	0.257	0.01128	0.029	74.26	25.33	0.005285

Expected Higgs mass resolution



Artificial Neural Network



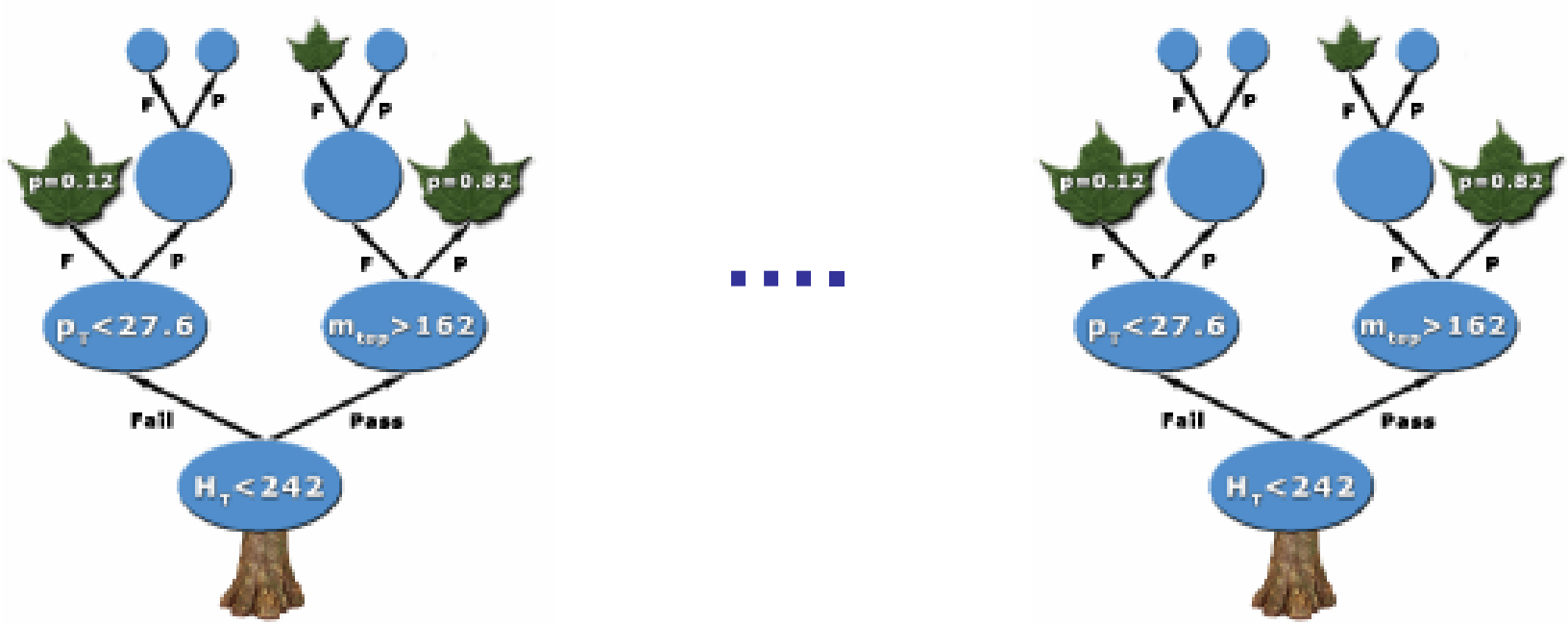
Neurons with response function

Input quantities (signal and background)

Output

The neuron response function parameters are optimized by minimizing an error function which requires that the output value of signal events is close to 1 and that of the background events is close to 0

Decision Tree (Forest)



Construct a tree from known (e.g. MC) Signal and Background type events.
At every branch choose quantities and cuts resulting in best Signal—Background separation.
Stop on leafs at given signal purity (or minimum number of events).
Leafs are “Signal” or “Background” depending the majority of event type landed on it.
Build a next tree and eventually a forest – an ensemble of trees using different event weights.
An event gets a large weight if it is misclassified by the previous tree (boost).
An event of unknown type (e.g. data) is scored 1 or 0 if landing on “S” or “B” type leaf in a tree.
Its final score of the forest is the average score of the individual trees

Calculation of the Bayesian posterior probability p(R|N)

Combined likelihood with flat prior $\pi(\theta_k)$:

$$\mathcal{L}(R,\vec{s},\vec{b}|\vec{n},\vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}}/n_{ij}! \times \prod_{k=1}^{n_{np}} e^{-\theta_k^2/2}$$

$\mu_{ij} = R\, s_{ij} + b_{ij}$

s_{ij} and b_{ij} are the expected SM signal and background in channel i and bin j

p(R|N) is the integral of the likelihood $\mathcal{L}$ over all variables except R

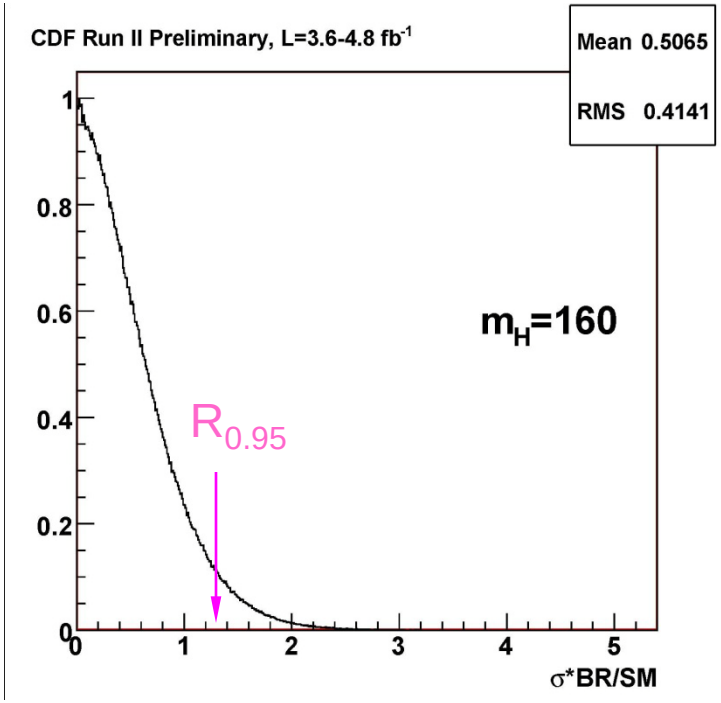
The CDF method

aka Bayesian method

Calculates Bayesian posterior probability of R, p(R|N) with a flat prior π(R)=const where $R=(\sigma \times BR)/(\sigma \times BR)_{SM}$ and N is the ensemble of the observed number of events in all bins of the final variable distributions in all analysis channels

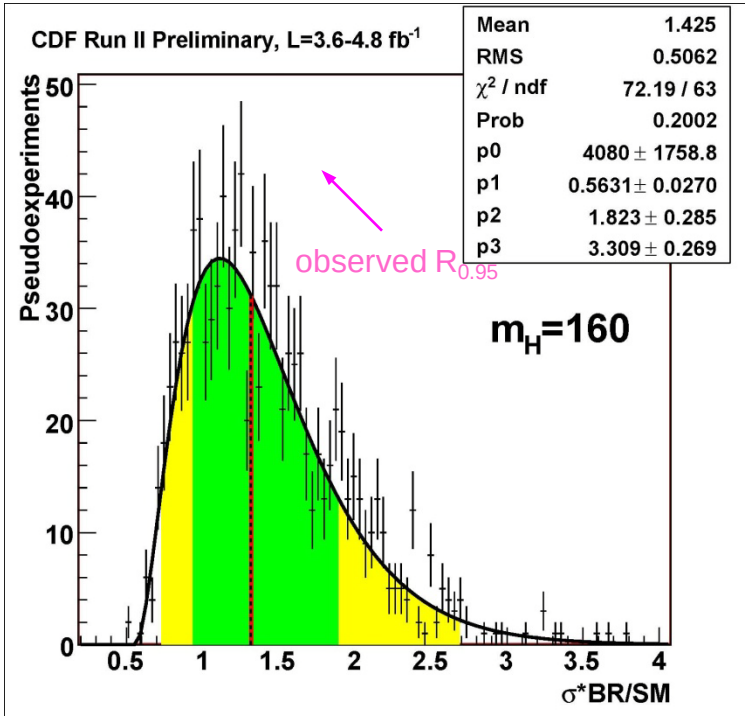
Determine $R_{0.95}$ defined as $\int_0^{R_{0.95}} p(R|N)dR = 0.95$

Integrate over the uncertainties of
all nuisance parameters:
Luminosity
Energy scales
Object id efficiencies
Fake rates
Other model parameters, etc.

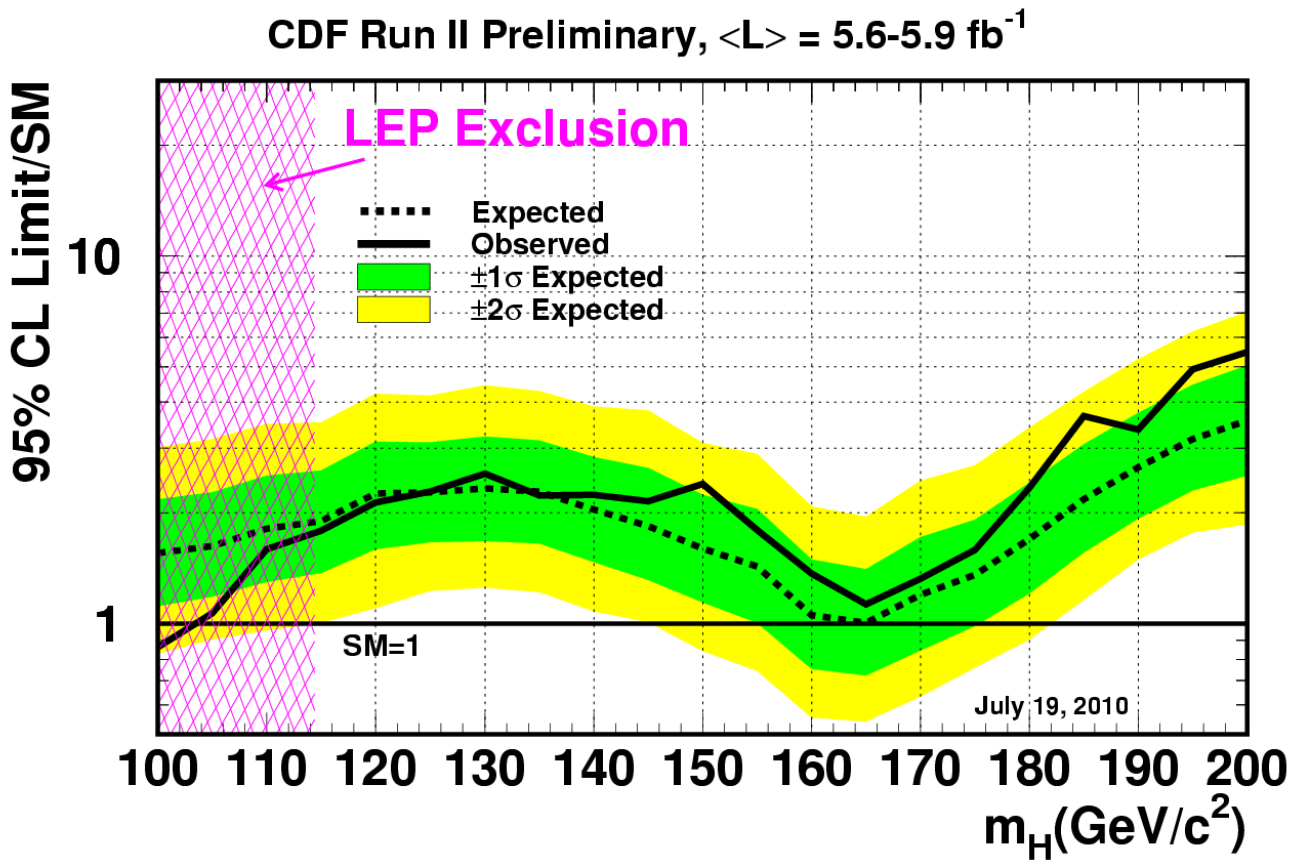


Determine also $R_{0.95}$ on 1000 background only Poissonian pseudo experiments for each mass point and for each analysis to compare with observed $R_{0.95}$

Repete for all mass points



CDF combined limit



R

M_H(GeV)	115	165
Expected	1.90	1.00
Observed	1.79	1.13

The D0 method

aka semi-frequentist or CLs method

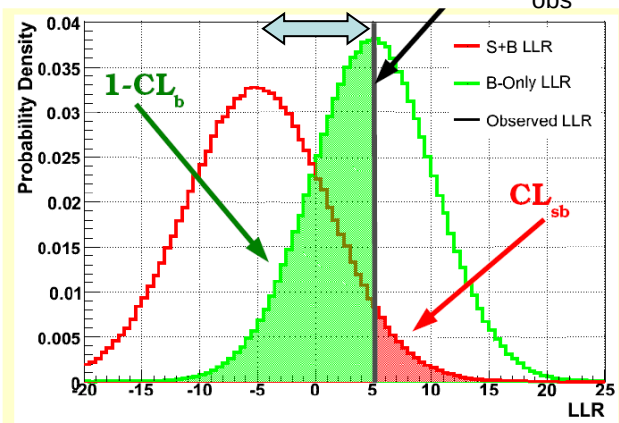
Log-Likelihood-Ratio (LLR) as test statistics: $LLR = -2\ln\frac{P(N|H_1)}{P(N|H_0)}$

H_0 and H_1 - test hypotheses of background w/o and w/ signal
N - ensemble of number of events
P - Poissonian pdf of N: $P = e^{-\mu}\mu^N/N!$
includes pdf of nuisance parameters θ: $\exp[-\frac{(\theta-\theta_0)^2}{2\sigma_\theta^2}]$

Profiling:
LLR is minimized wrt the nuisance parameters

LLR_{obs} = LLR(N=Data)
LLR_b = LLR(N=Background)
LLR_{sb} = LLR(N=Signal+Background)

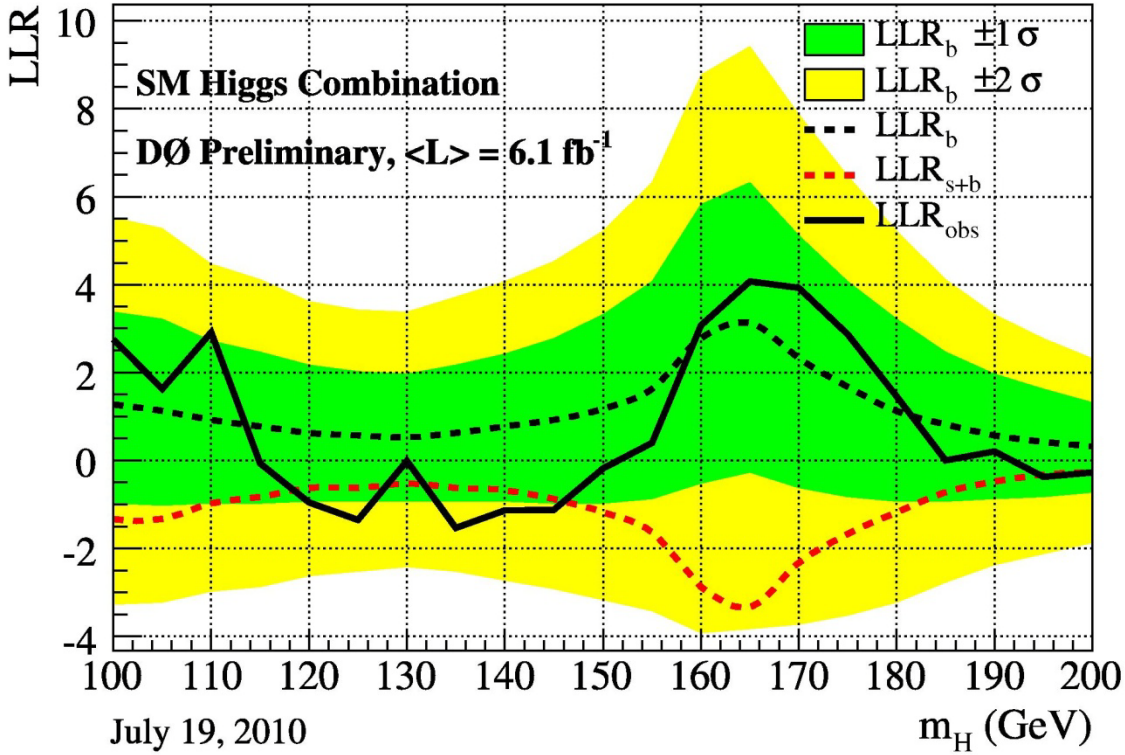
signal—background separation



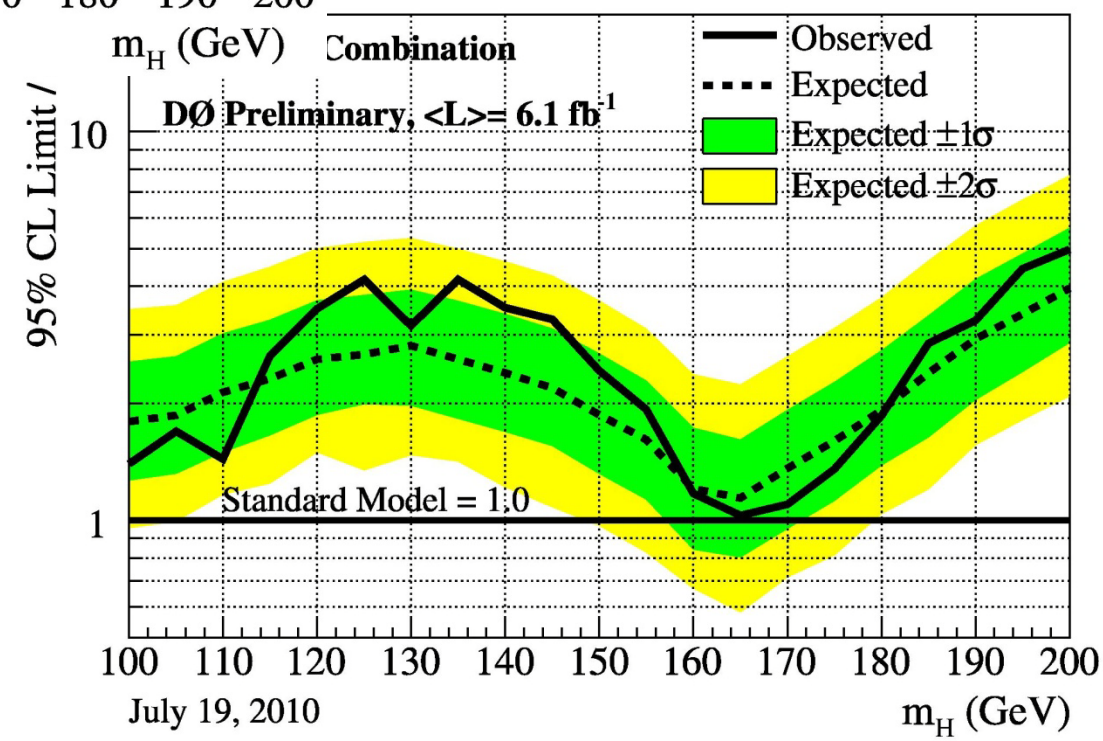
Confidence levels:
$1\text{-}CL_b = p(LLR_b < LLR_{obs}|H_0)$
$CL_{sb} = p(LLR_{sb} > LLR_{obs}|H_1)$
$CL_s = CL_{sb}/CL_b$

A signal $R=(\sigma x BR)/(\sigma x BR)_{SM}$ is excluded @ 95% CL if $CL_s(R)= 0.05$ i.e. $1\text{-}CL_s(R)= 0.95$

It has been checked that the Bayesian and CLs methods give comparable results (~10%)



D0 combined limits

R

M_H(GeV)	115	165
Expected	2.31	1.14
Observed	2.65	1.03