SM Higgs boson studies at the Tevatron

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On behalf of CDF and Dzero

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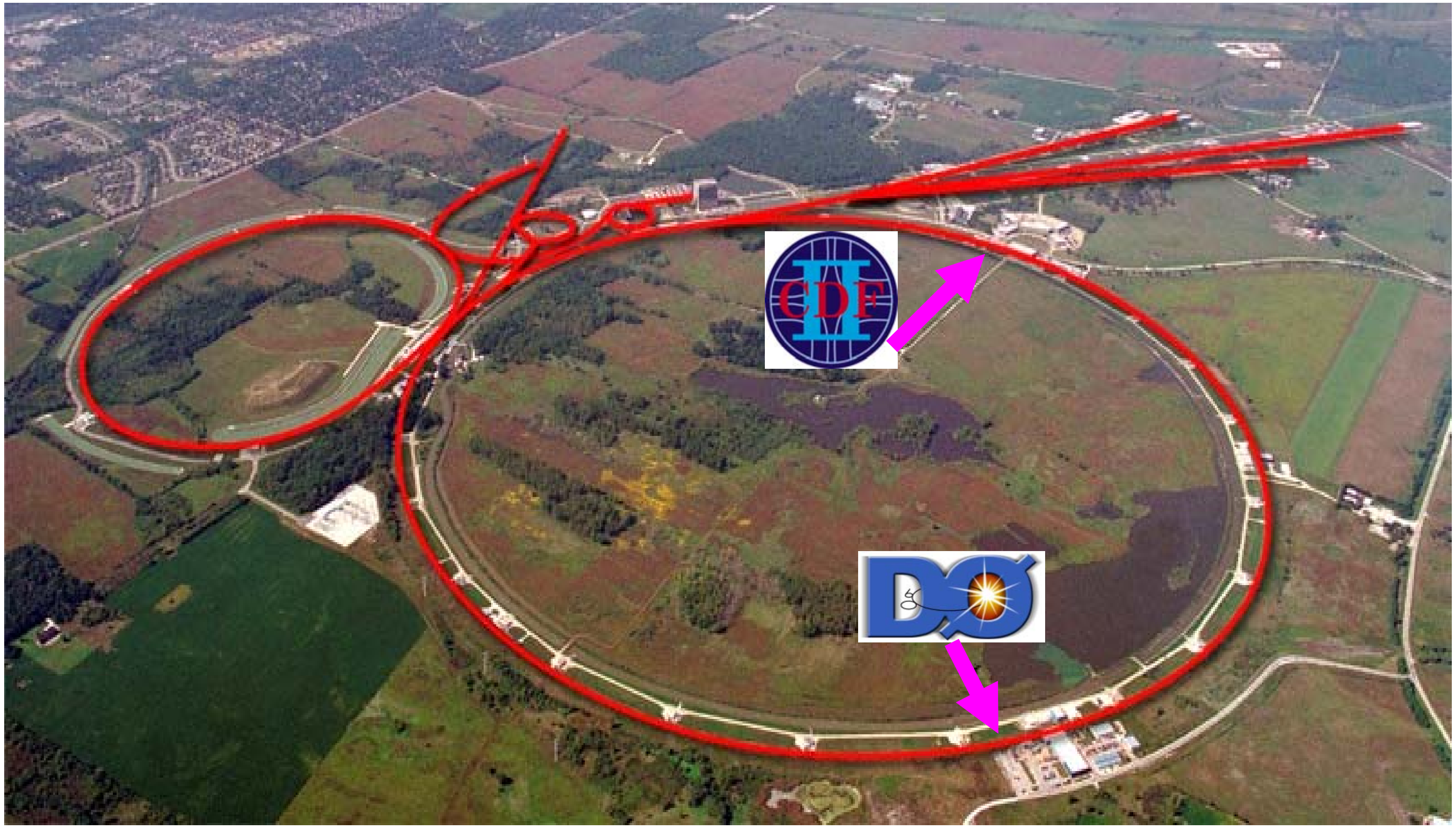
Thanks to all CDF & DZero colleagues,
Special thanks to L. Zivkovic

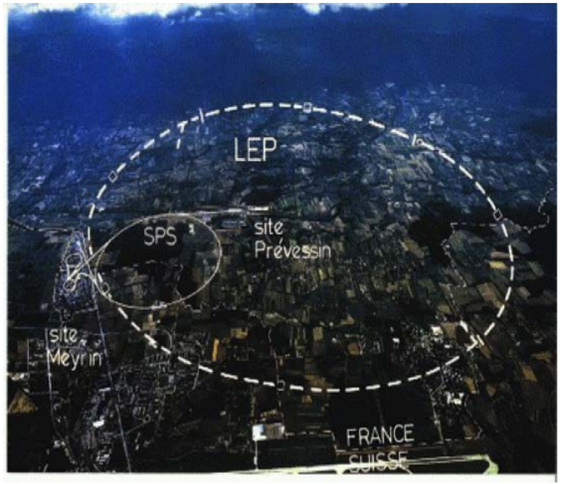


Outline

- **Historical perspectives/Current situation**
- **Low mass (H→bb) Higgs searches**
- **Combinations of Standard Model searches**
- **Higgs Couplings**
- **Prospects**

All Final individual channels and combinations from CDF and D0 are published or submitted.

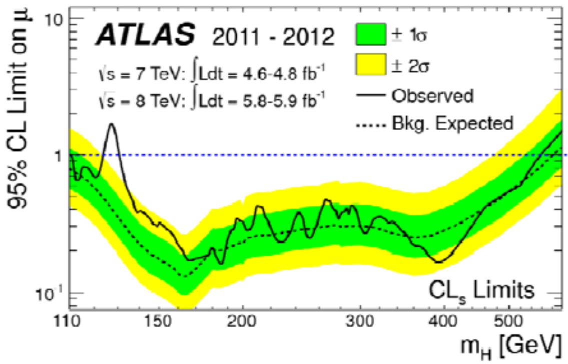
Historical perspective (→ summer 2012)

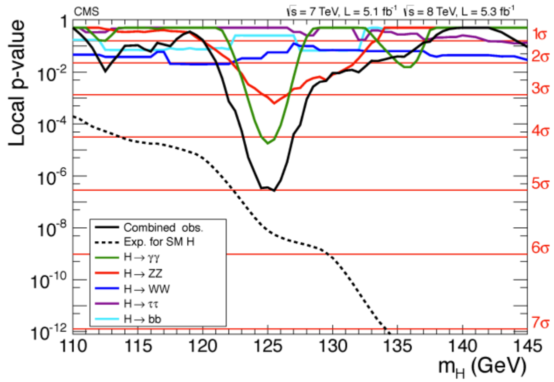


- **LEP (1989 - 2000): m_H > 114.4 GeV@95% CL**

- **At hadron colliders:**
- **Tevatron Run II (2002 - 2011):**
  - First post-LEP 95%CL exclusion (july 2009)
  - First evidence of a Higgs-like particle decaying to a pair of b-quarks (July 2012)

- **LHC (2010 - 2012):**
  - Excluded wide mass range (111 – 122 GeV and 127 – 600 GeV)
  - Discovered the new Higgs-like boson mainly through γγ and ZZ decays (July 2012)



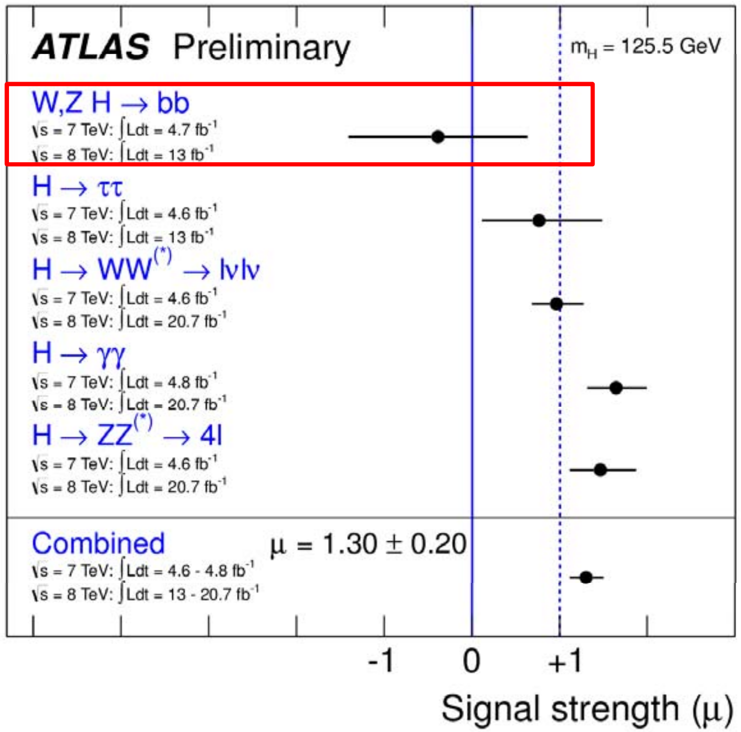


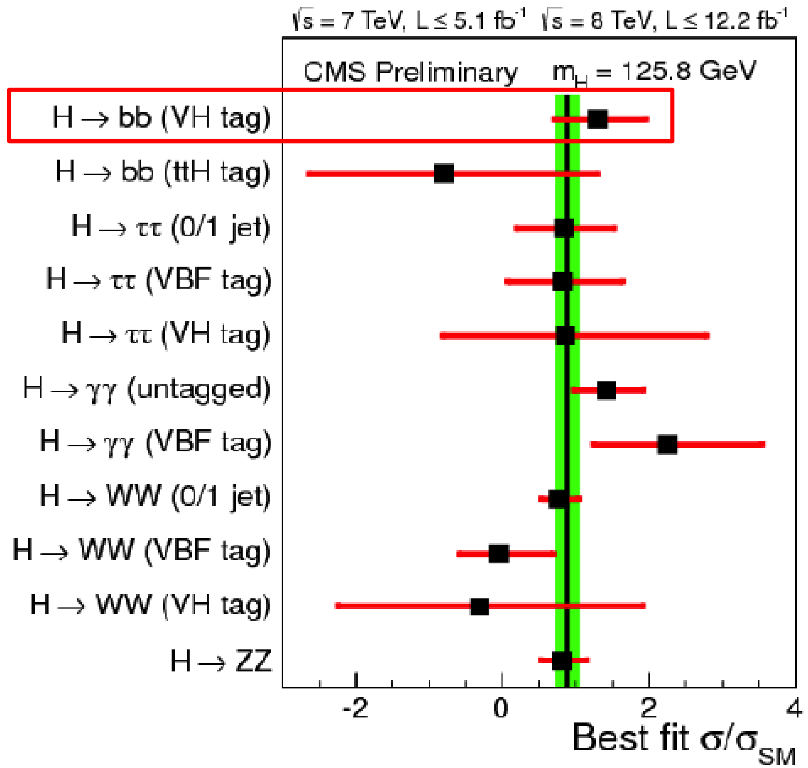
Current situation

- **LHC (2011 – 2012):**
  - **Since July 2012 progress in each channel**
  - **Observation confirmed in bosonic channel**
  - **ATLAS: m_H = 125.5 ± 0.2 (stat) ± 0.6 (sys) GeV**
  - **CMS: m_H = 125.8 ± 0.4 (stat) ± 0.4 (sys) GeV**
  - **H→bb, with ~18 fb^{-1} : data deficit at Atlas and ~2.2 σ excess at CMS**
  - **strong indications (2.9 σ)of fermionic decays at LHC from CMS H→$\tau\tau$(full stat) but low ATLAS signal (1.1σ, 1.7σ expected, 18fb^{-1})**

As presented at Moriond and Aspen

➔ **While it "is" a Higgs boson, the fermionic decays are not firmly established.**





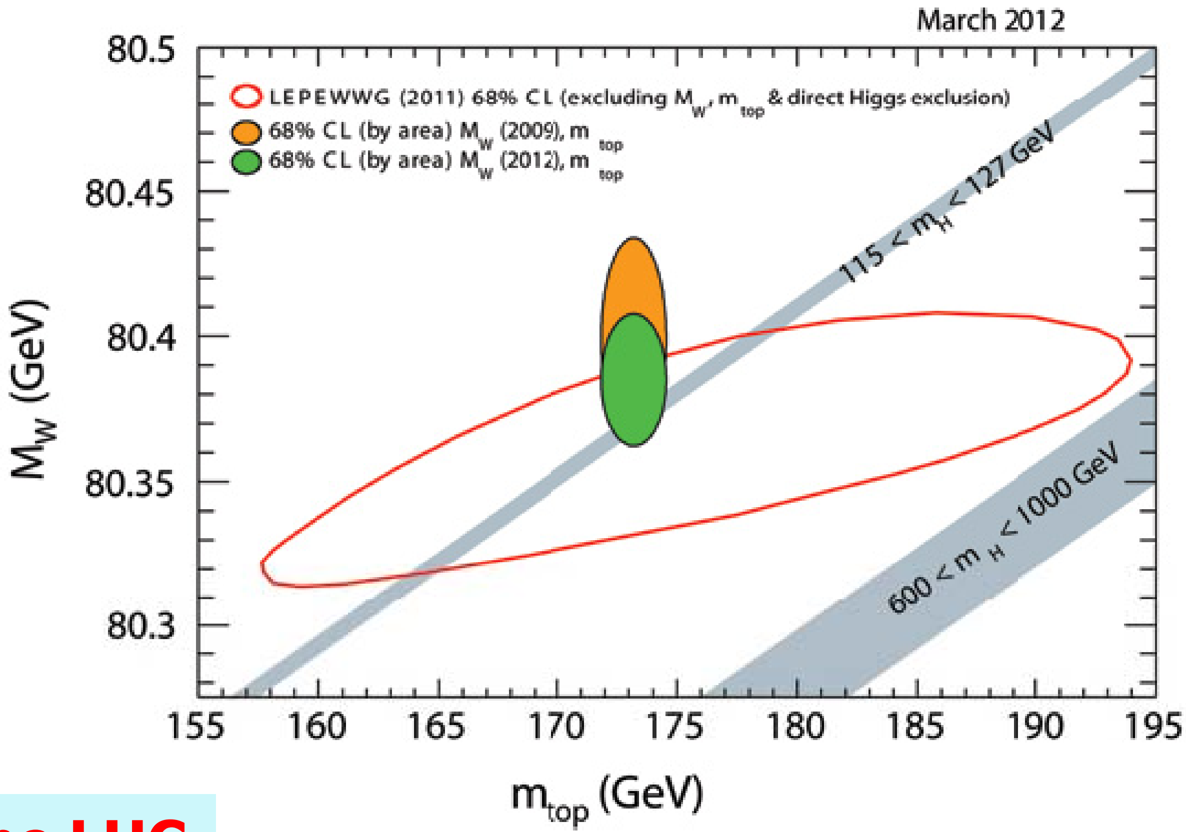
Indirect SM Higgs constraints

Recently updated top quark and W boson mass measurements from the Tevatron

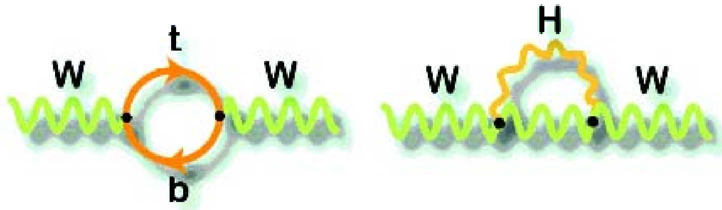
$m_W = 80385 \pm 15$ MeV

$m_t = 173.2 \pm 0.9$ GeV

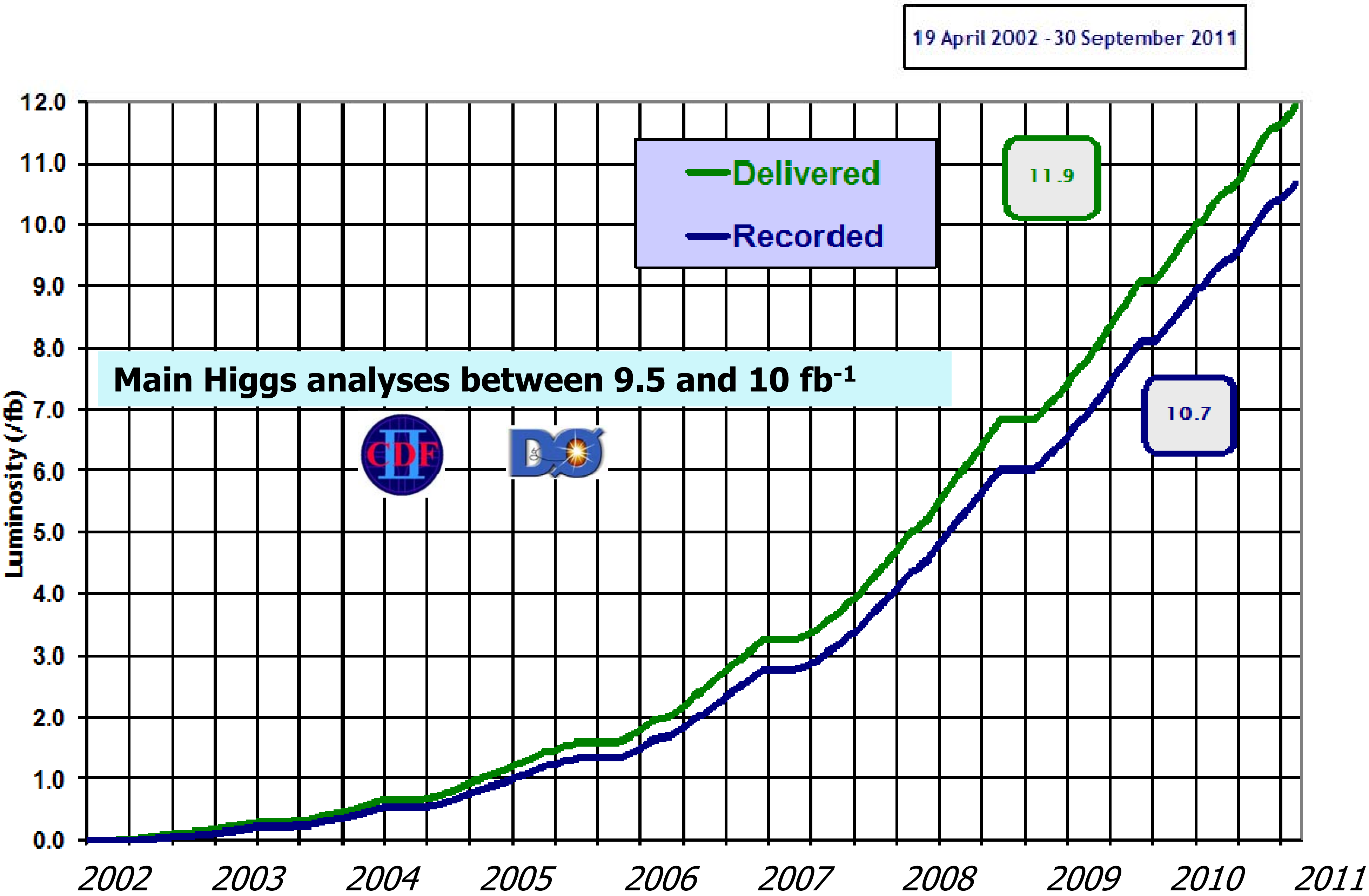
(LHC getting close on top mass)



The boson discovered at the LHC looks like the SM Higgs also from the indirect point of view
➔ Tevatron update on W mass will provide further constraints

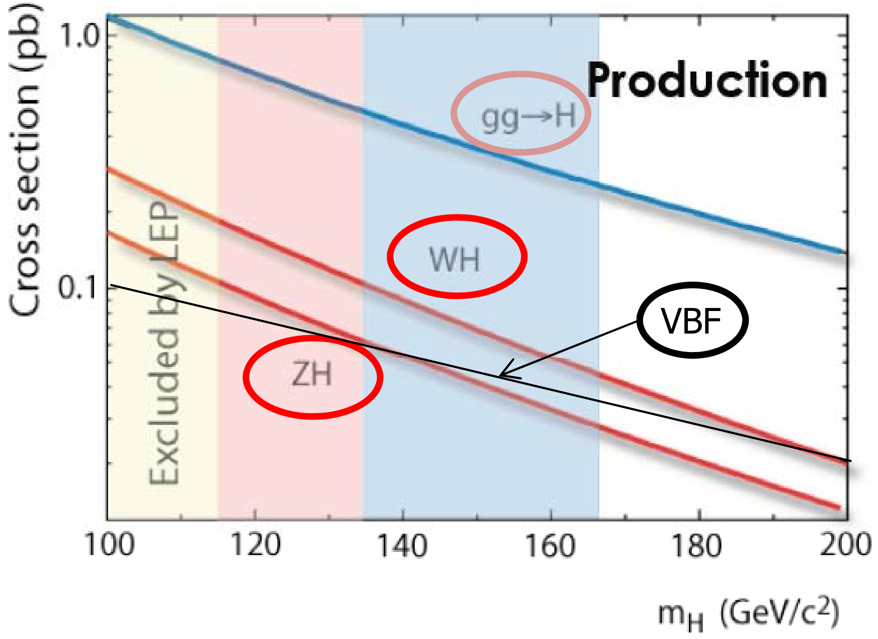


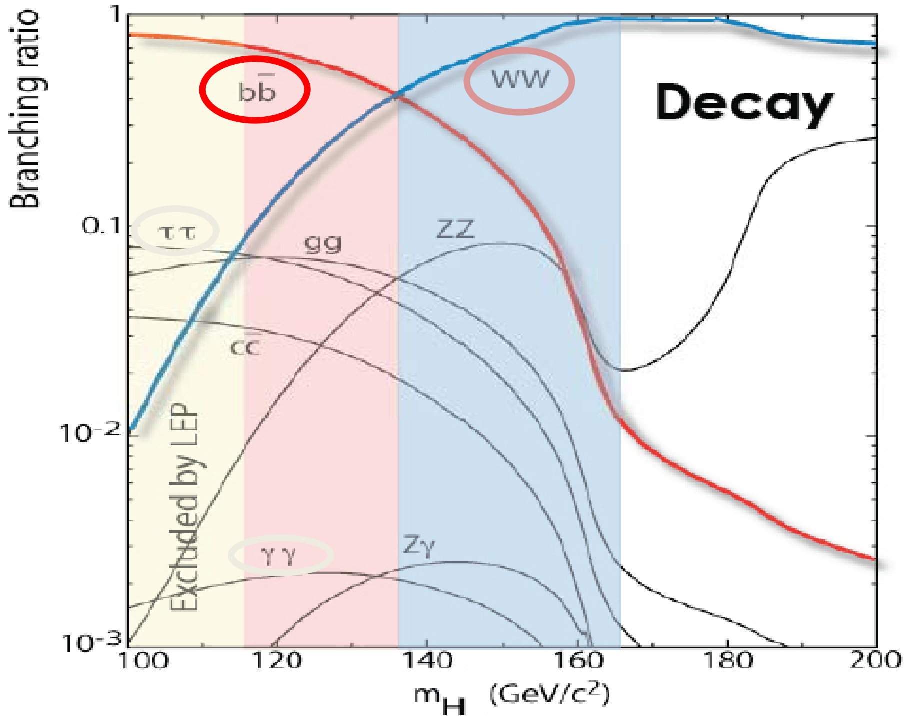
Tevatron Luminosity



Thanks to the Tevatron Accelerator Group for such a performance!

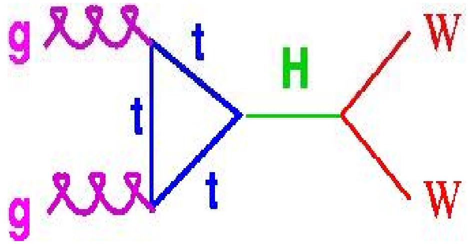
Higgs Production and Decay at the Tevatron





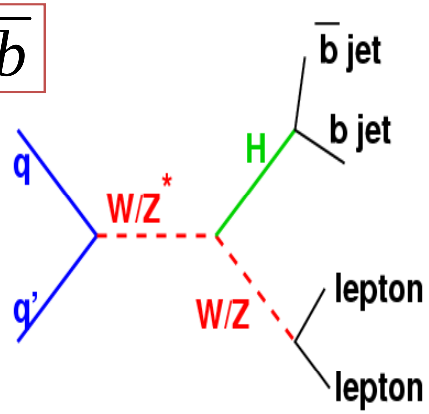
"High" mass (m_H > 135 GeV) dominant decay:

$H \to WW^{(*)}$ $\quad gg \to H \to WW \to \ell \nu \ell' \nu'$



Low mass (m_H < 135 GeV) dominant decay:

$H \to b\bar{b}$



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

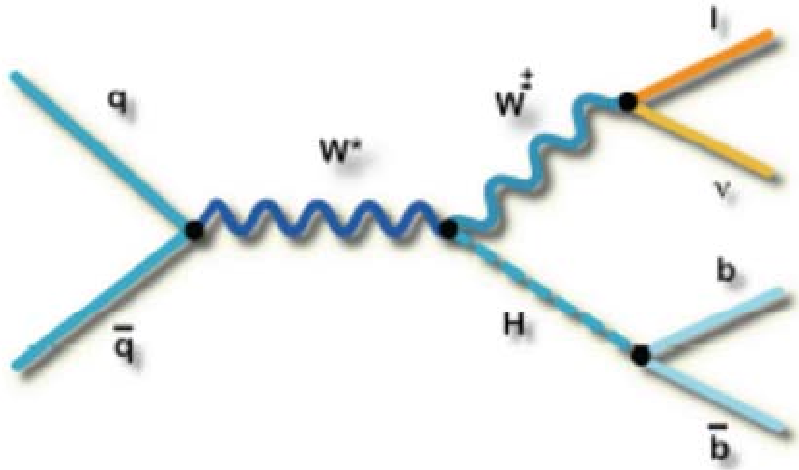
$ZH \to \ell^+ \ell^- b\bar{b}$

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

use associated production modes to get better S/B

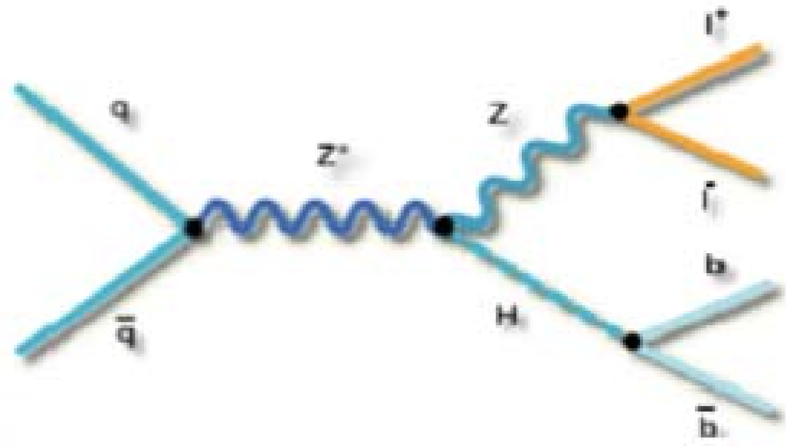
These are the main search channels, but there is an extensive program of measurements in other channels to extend the sensitivity to a SM Higgs

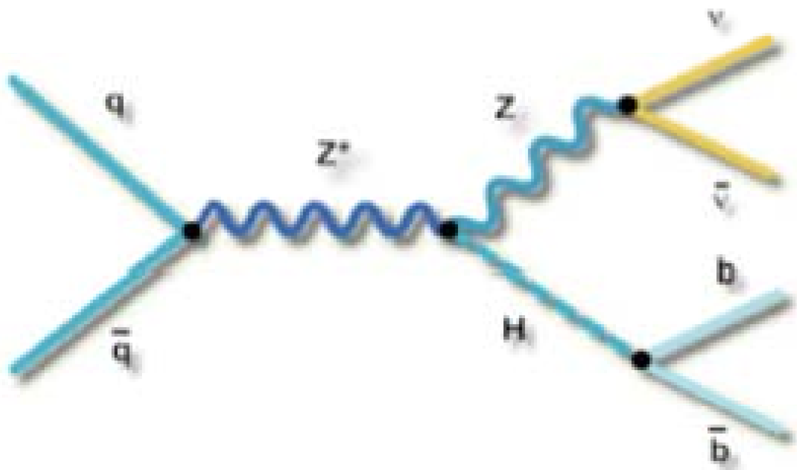
Low Mass Higgs Channels



WH→lνbb: MET+l+bb
Large production cross section
Higher backgrounds than in ZH→llbb

ZH→llbb: ll+bb
Low background
Fully constrained
Small Signal



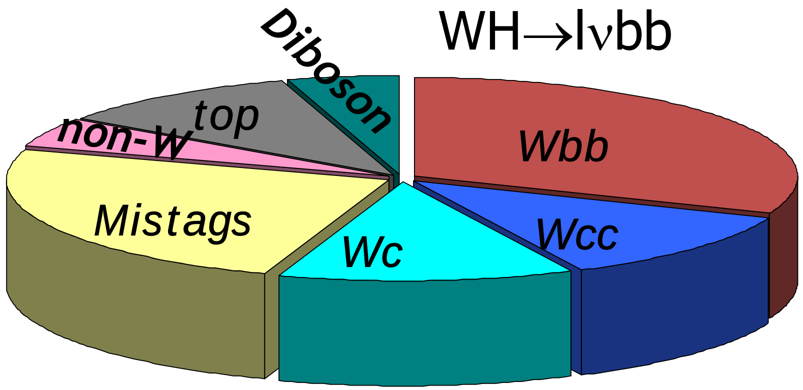


ZH→ννbb: MET+bb
signal 3x larger than ZH→llbb
(+ contributions from WH)
difficult backgrounds

Low Mass Higgs Searches

Increase lepton reconstruction and selection efficiencies

Understand background



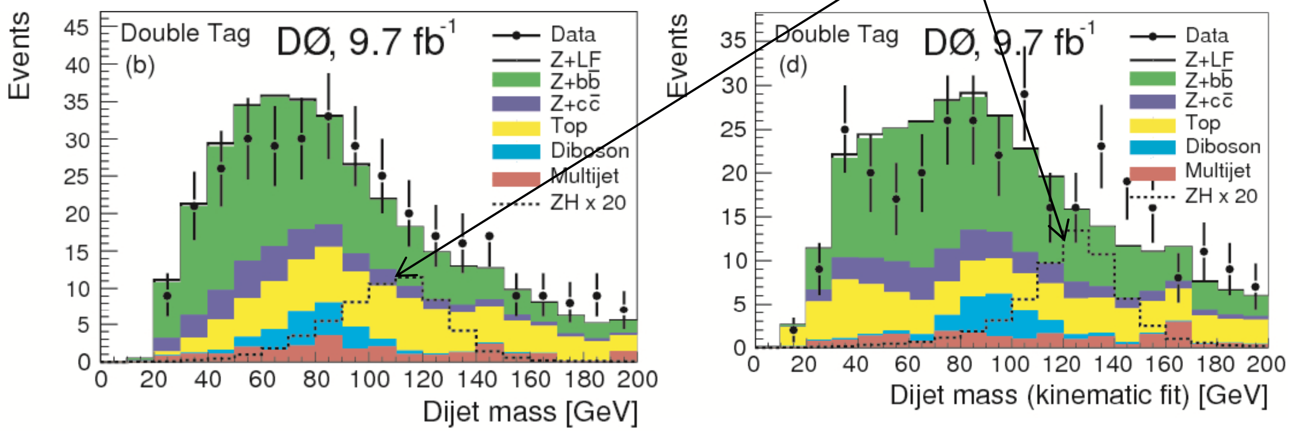
Specific to low mass analyses:

B-tagging (next slide)

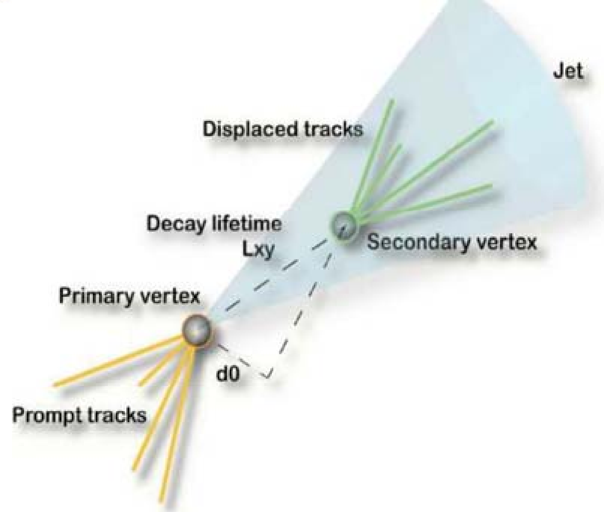
Optimize dijet mass resolution

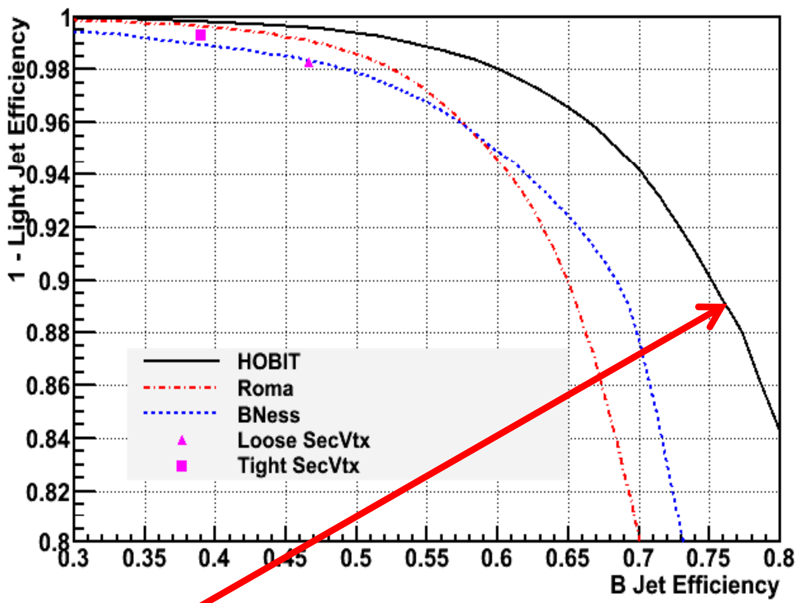
➔ needs precise calibration and resolution for gluon and quark jets separately
➔ new techniques still explored (NN, tracks + calorimeter cells)

We also optimize dijet mass resolution with Kinematic fit in ZH→llbb (15% sensitivity gain)



Low Mass Higgs Searches





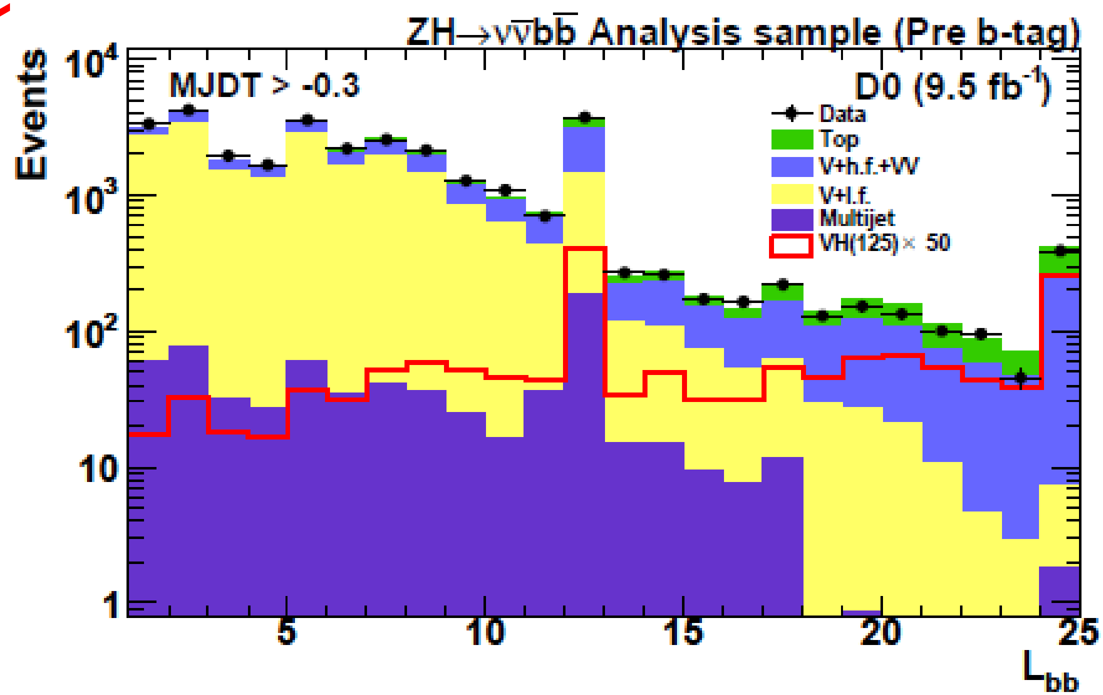
75% eff. for 10% mistag
42% eff. For 0.9% mistag

Reduce the background by tagging b-quark jets

Major step forward with HOBIT, MVA tagger @ CDF (D0 already use one)

- separate b-jet from light-jets

24 operating points allows for s/b optimizations in sub-samples ➔



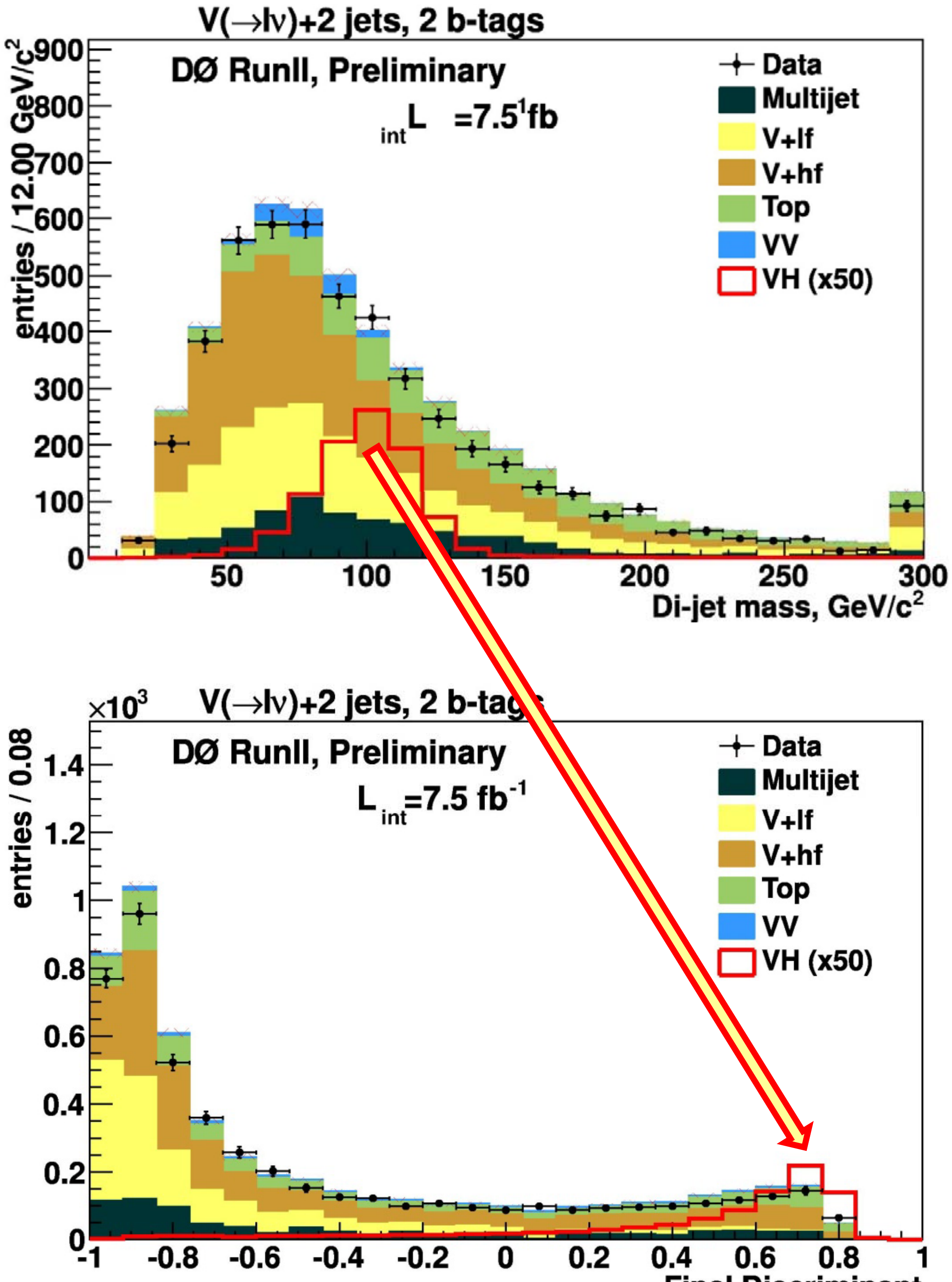
- next step would be to separate b from c with dedicated algorithm

From Dijet mass to Multi Variate Analysis

- **To improve S/B ➔ utilize full kinematic event information**
- **Multi Variate Analyses**
  - Neural Networks
  - Boosted Decision Trees

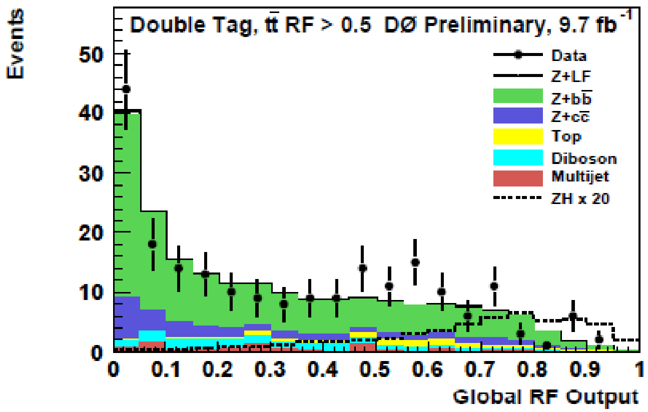
  Or use Matrix Element Calculations to determine probability for an event to be signal or background like

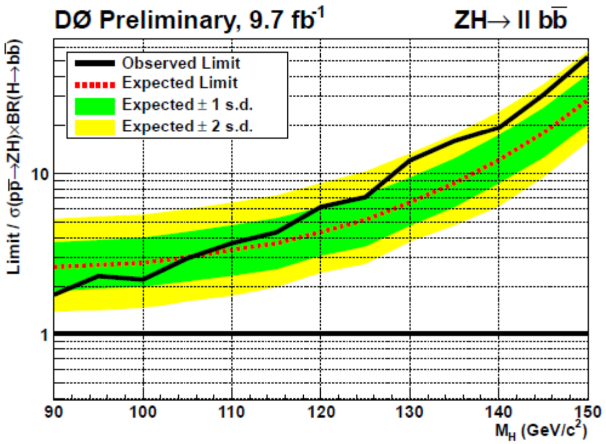
- **Approaches validated in Single Top observation @ Tevatron**
- **Combine these approaches**
- **Visible gain obtained (~25% in sensitivity)**



Latest Results from DØ

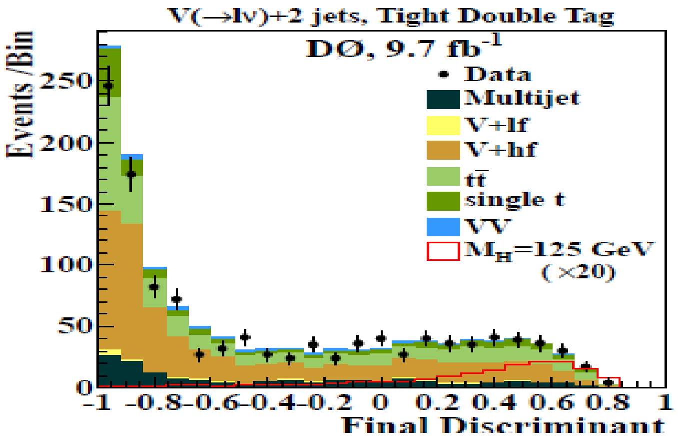
ZH→llbb̄ ∫Ldt=**9.7**fb^{-1}

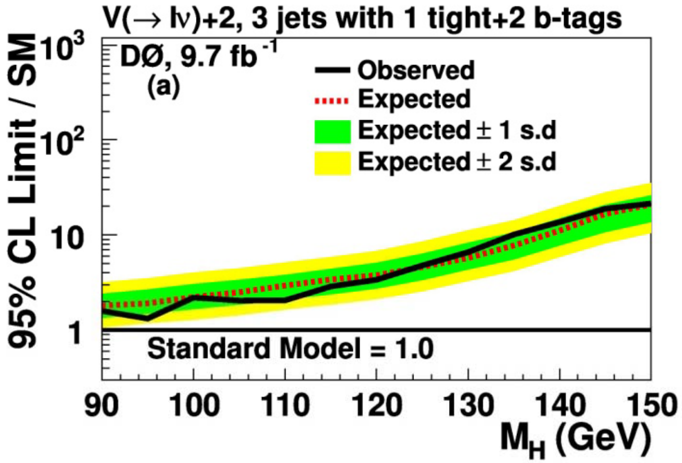




95% CL Exp (obs)
Limit **5.1** (**7.1**) x SM
@ MH=125 GeV

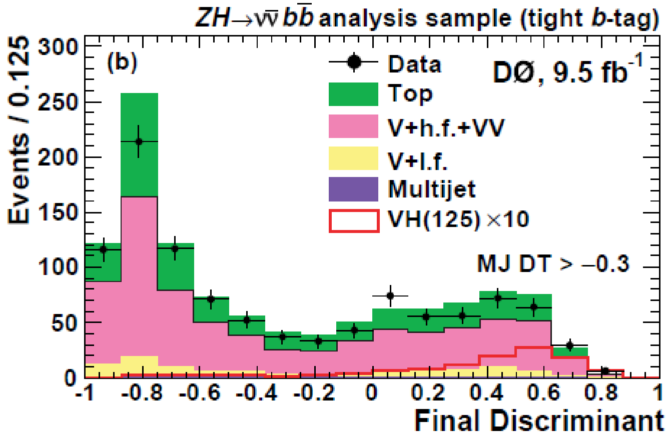
WH→lνbb̄ ∫Ldt=**9.7** fb^{-1}

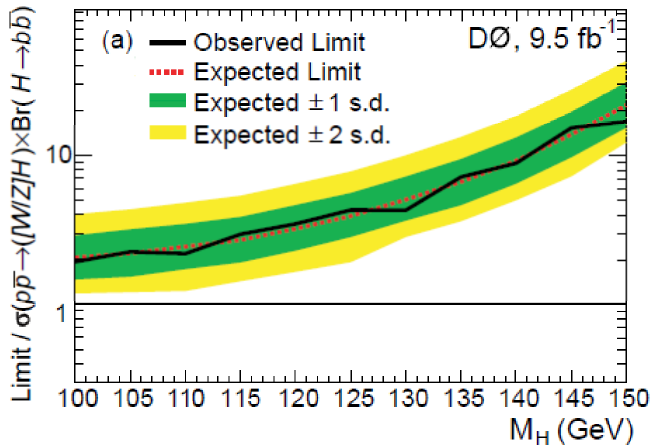




95% CL Exp (obs)
Limit **4.7** (**4.8**) x SM
@ MH=125 GeV (updated 01/13)

ZH→ννbb̄ ∫Ldt=**9.5** fb^{-1}



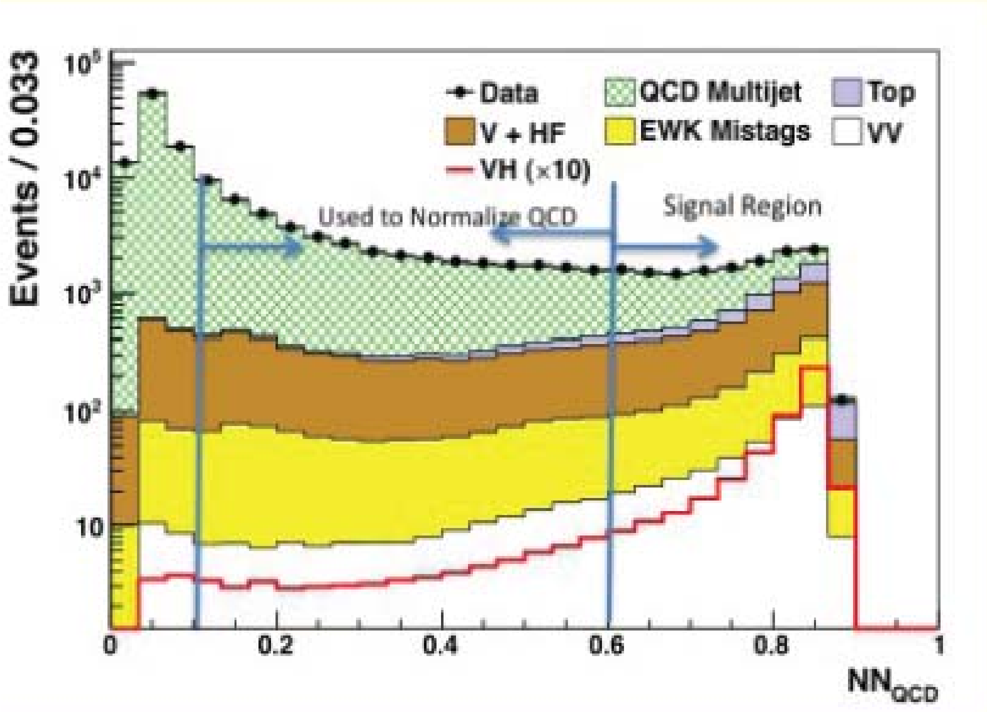


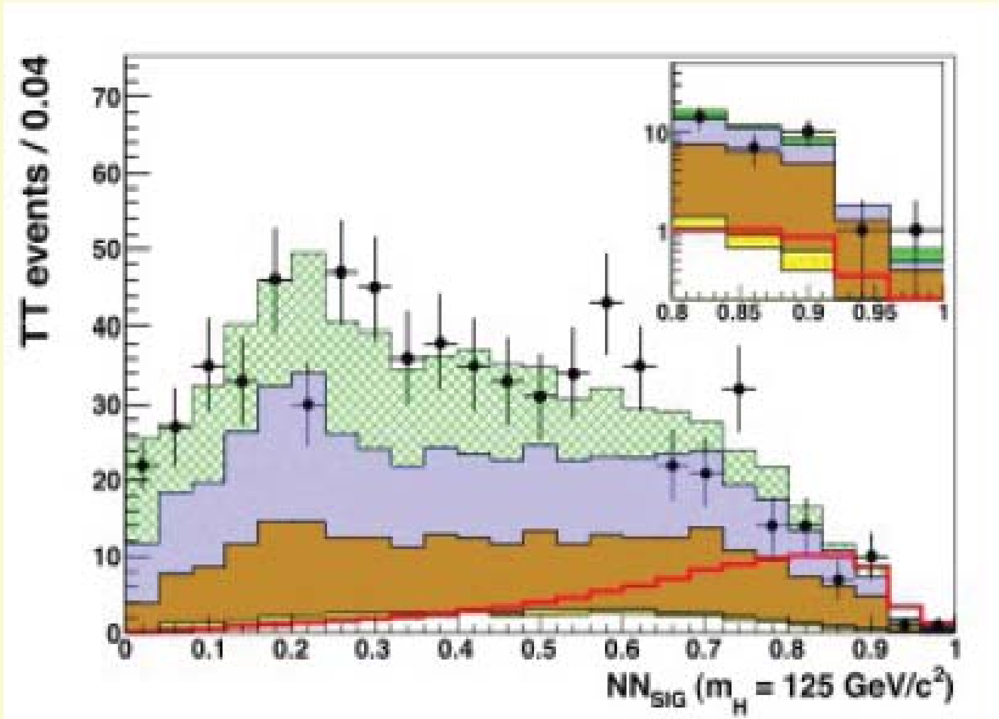
95% CL Exp (obs)
Limit **3.9** (**4.3**) x SM
@ MH=125 GeV

~10-15% gain on intrinsic sensitivity compared to Moriond 2012 result (i.e. on top of gain due to luminosity)

Updated $\nu\nu bb$ (METbb) channel at CDF

- Reject Multijet background with dedicated Neural Network
- Separate signal from the remaining backgrounds using second NN

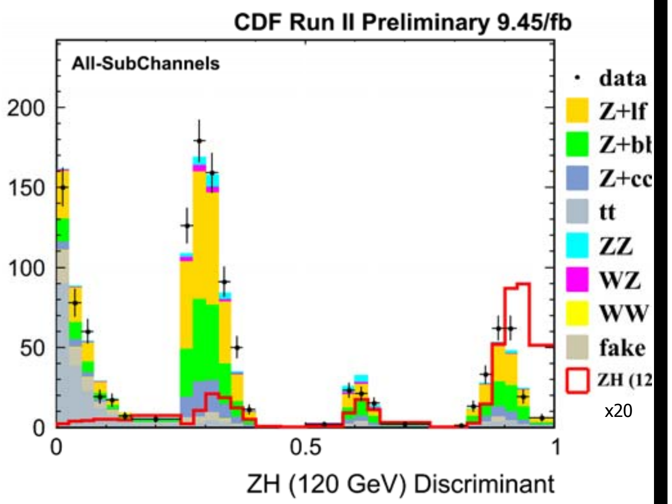


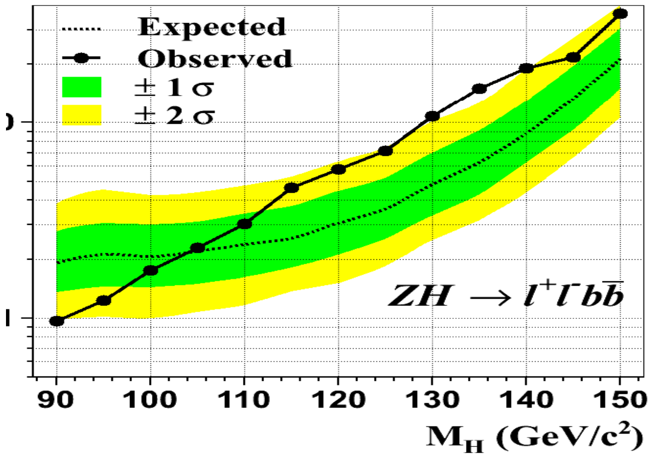


- At m_H=125 GeV: obs = 3.06*SM; exp = 3.33*SM
- 8% sensitivity improvement at m_H=125 GeV (Compared to July 2012)
- Average expected improvement over the whole mass range: 14%

Latest Results from CDF

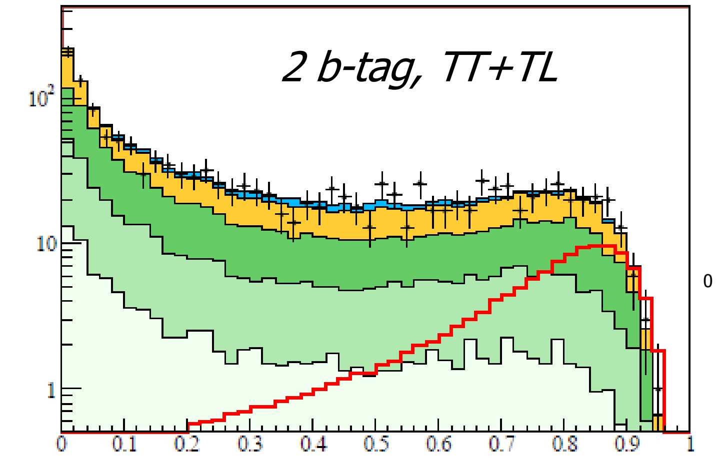
ZH→llbb̄ ∫Ldt=9.5 fb^{-1}

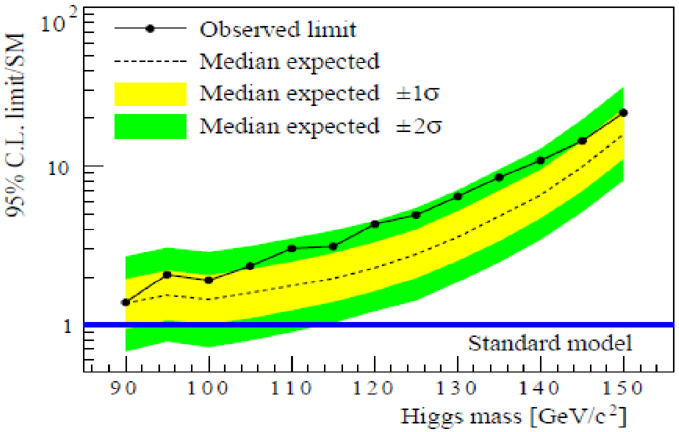




95% CL Exp (obs)
Limit **2.6** (**4.7**) x SM
@ MH=125 GeV

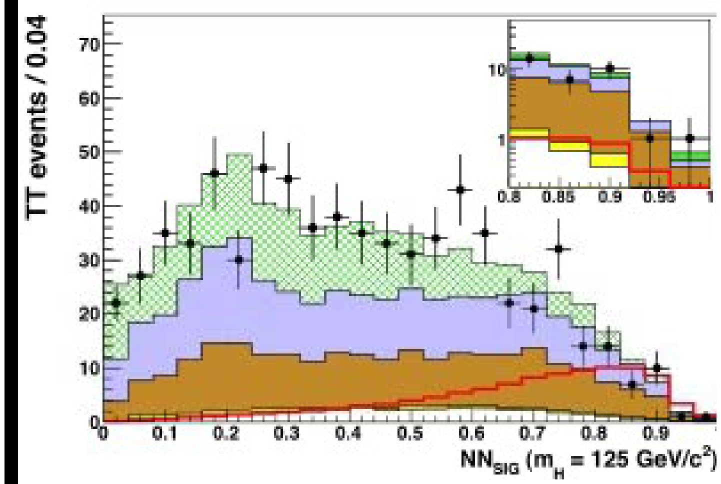
WH→lνbb̄ ∫Ldt=9.5 fb^{-1}

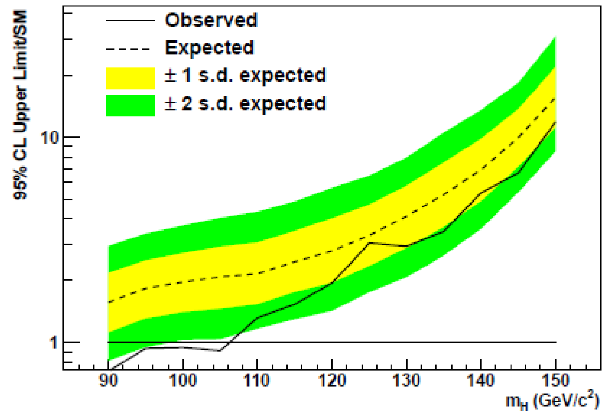




95% CL Exp (obs)
Limit **2.8** (**4.9**) x SM
@ MH=125 GeV

ZH→ννbb̄ ∫Ldt=9.5 fb^{-1}





95% CL Exp (obs)
Limit **3.3** (**3.1**) x SM
@ MH=125 GeV (updated 01/13)

>20% gain on intrinsic sensitivity compared to 2011

Cross check on Diboson process

Benchmark of H→bb searches with real data.

VZ→leptons + heavy flavor jets

For m_H=125 GeV

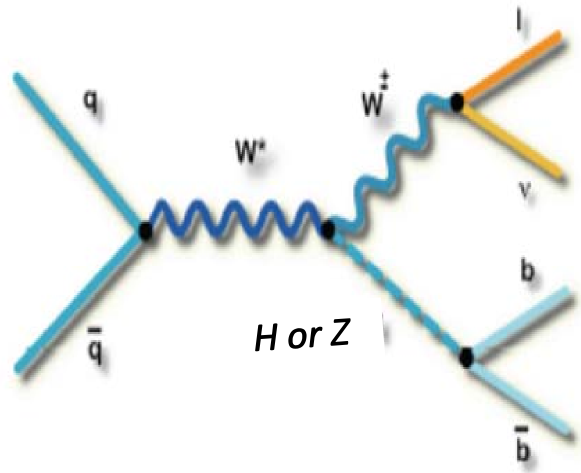
WH→lνbb: σ = 16 fb
ZH→ ννbb:σ = 9 fb
ZH→ llbb: σ = 3 fb

Total VH: σ = 28 fb

Replace H with Z

WZ→lνbb: σ = 105 fb
ZZ →ννbb: σ = 73 fb
ZZ → llbb: σ = 24 fb

Total VZ: σ = 202 fb

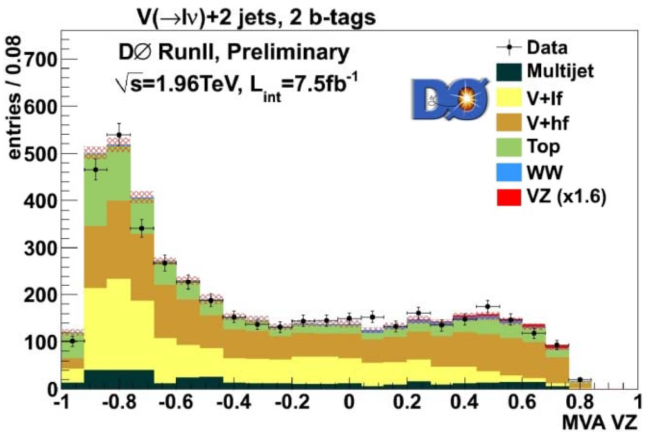


At 115 GeV, VZ yield is ~7 times larger than VH, but VZ→Vbb has much more W+jets backgrounds, and difficult background from WW, so VZ sensitivity only ~3 times higher than VH

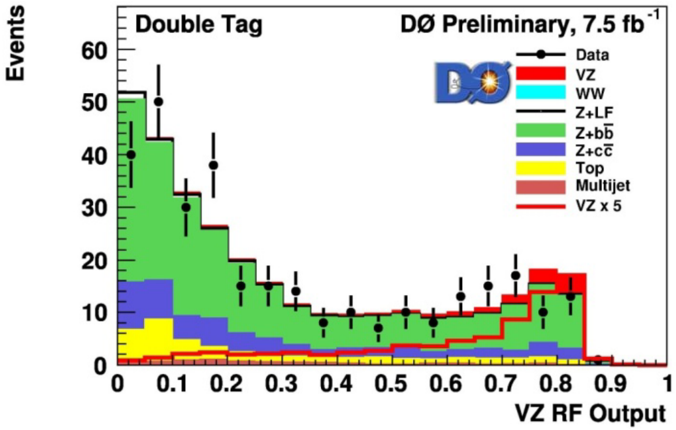
Apply similar analysis as low mass H→bb analysis, and check sensitivity.

Benchmarks : Dibosons to Heavy Flavor

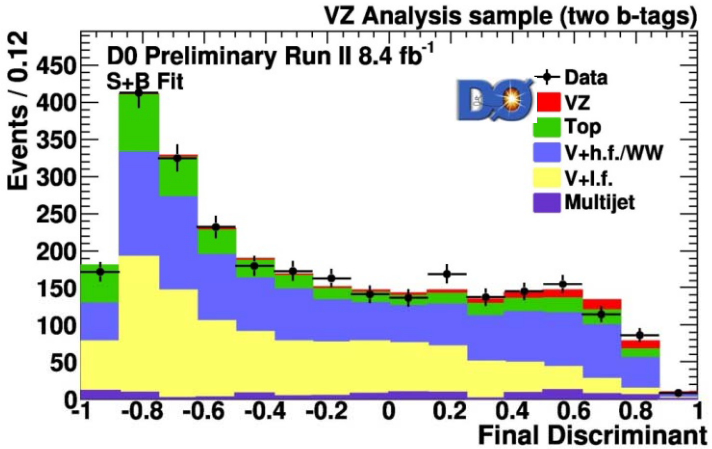
Diboson lvbb



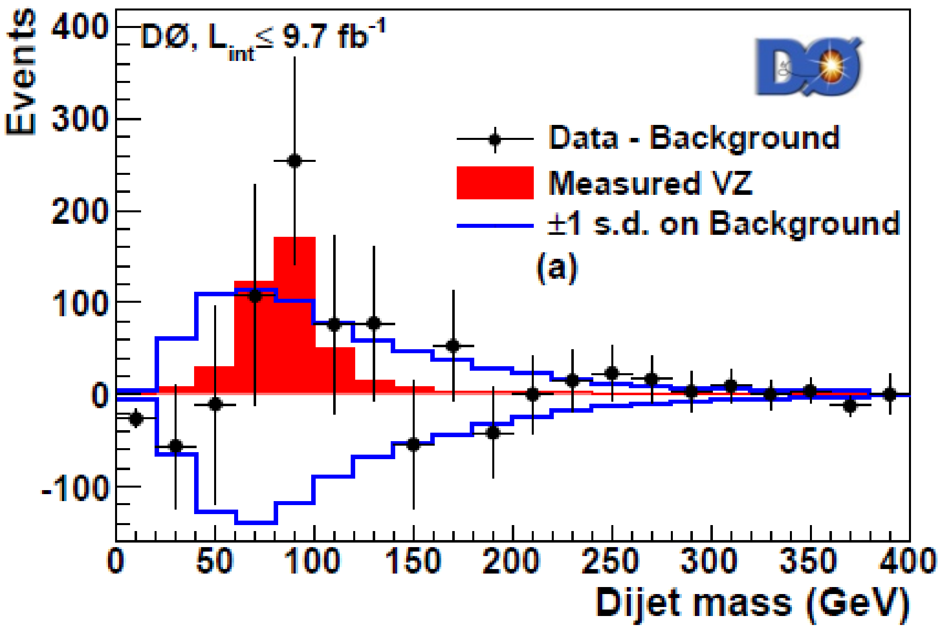
Diboson llbb

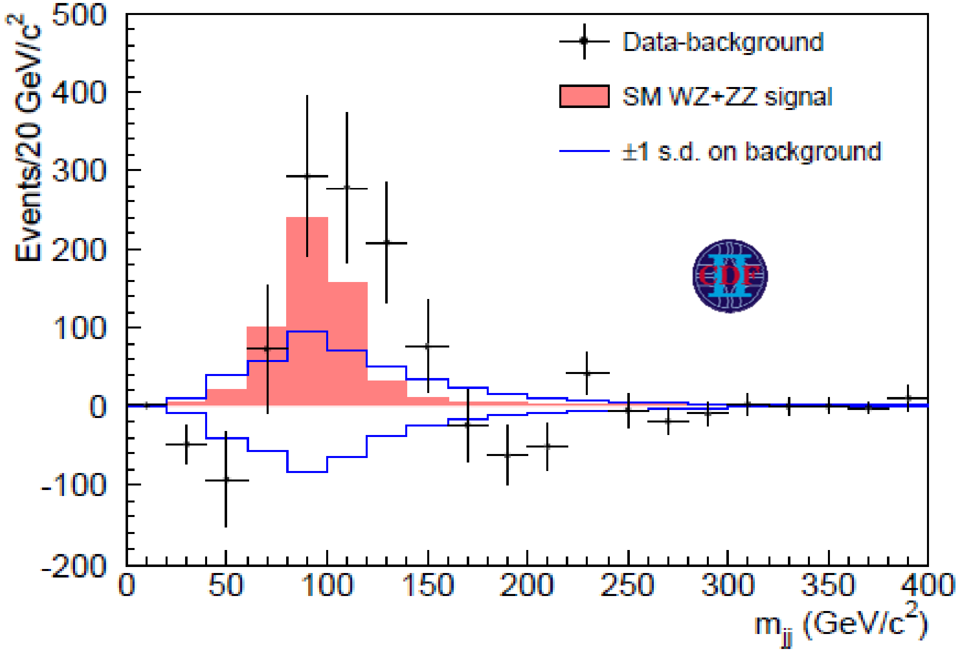


Diboson vvbb



Combining all three channels, maintaining proper correlation among channels, keeping WW as background, ➔ Evidence (>3 sigma / experiment) for WZ/ZZ decaying to H.F



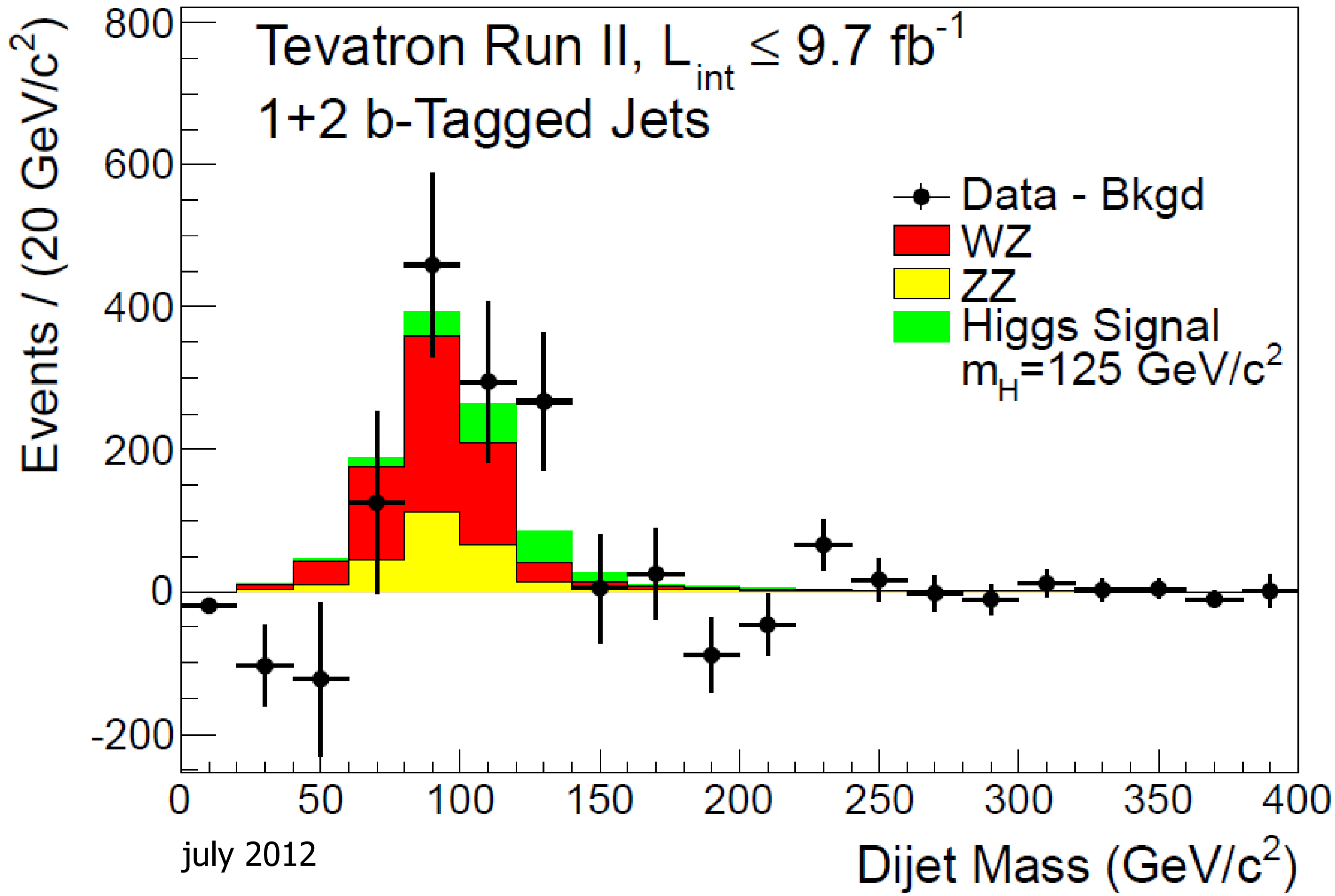


Benchmarks : Dibosons to Heavy Flavor

CDF- D0 combination on the same dataset/techniques as for H→bb:

→ ~ 4.5 sigma significance

cross-section: 3.9 +/- 0.9 pb (NLO: 4.4 +/- 0.3 pb)

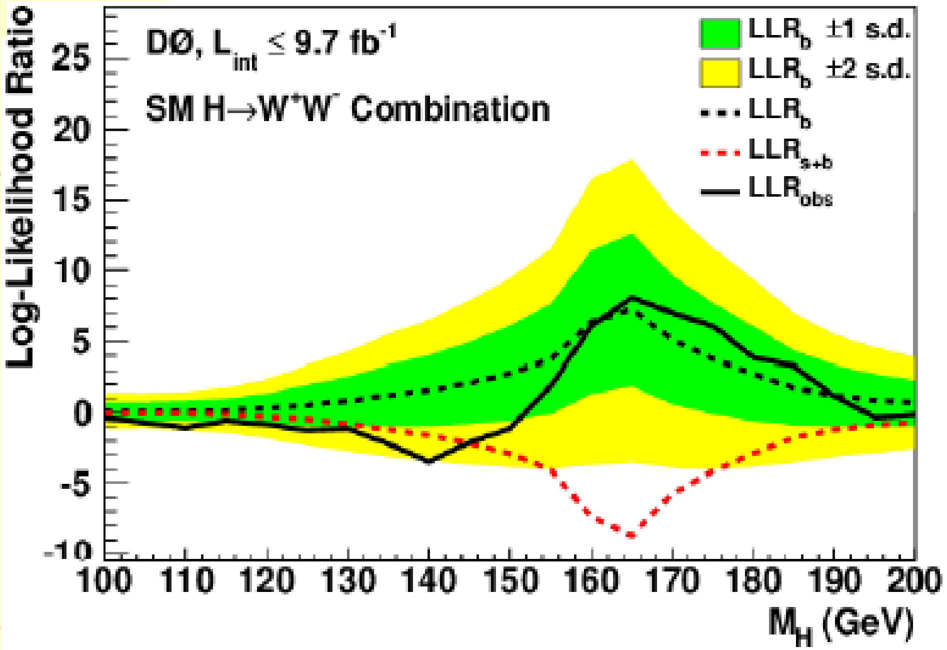


→ Since there is a light SM Higgs, we should "see" it!

Higgs Sensitivity / Log Likelihood Ratio plot

Background-like outcomes

Signal-like outcomes



$$LLR = -2\ln\frac{P(s+b)}{P(b)}$$

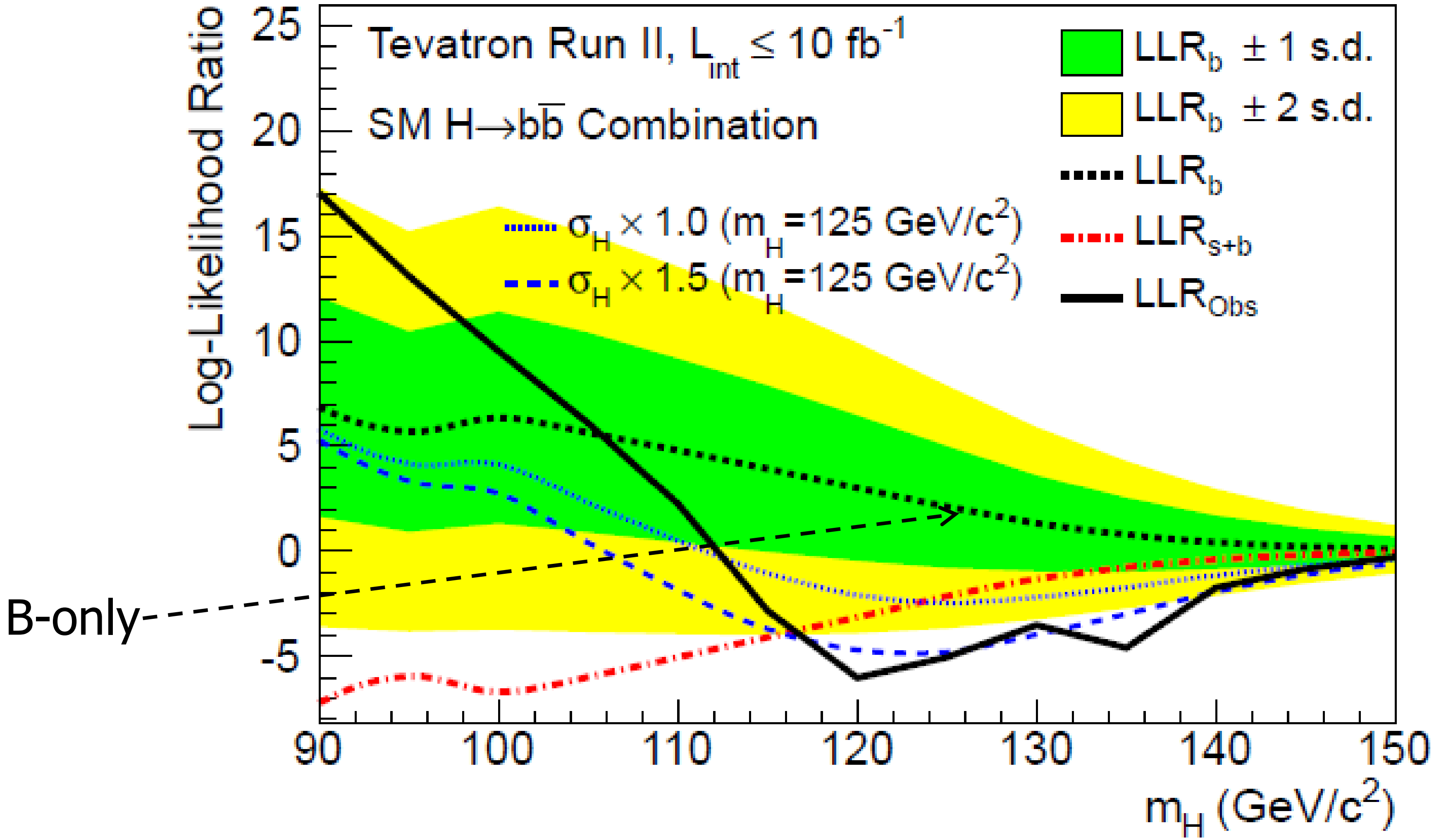
P - Poisson likelihood of B or S+B hypothesis

The separation between LLR_b (background-only hypothesis) and LLR_{s+b} (signal-plus-backgroundhypothesis) provides a measure of the discriminating power of the search

The width of the LLR_b, distribution (1 s.d. and 2 s.d. bands) provides an estimate of how sensitive the analysis is to a signal-like background fluctuation in the data, taking account of the presence of systematic uncertainties

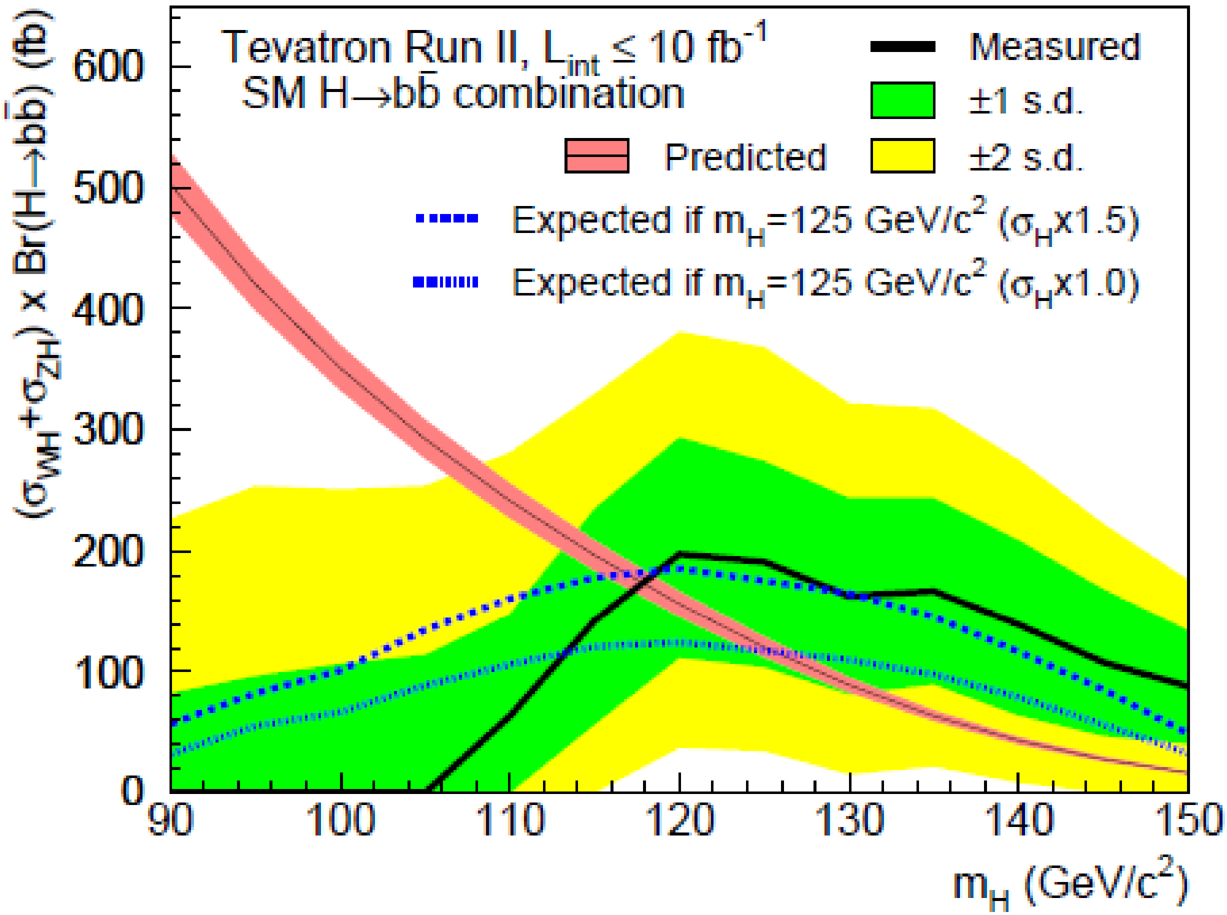
The value of LLR_{obs} relative to LLR_{s+b} and LLR_b indicates whether the data distribution appears to be more like signal-plus-background or background-only.

Combined Log-Likelihood Ratio for H→bb



Shape consistent with LLR expected in presence of 125 GeV Higgs, prefers slightly stronger strength than SM

Combined Cross section * BR measurement

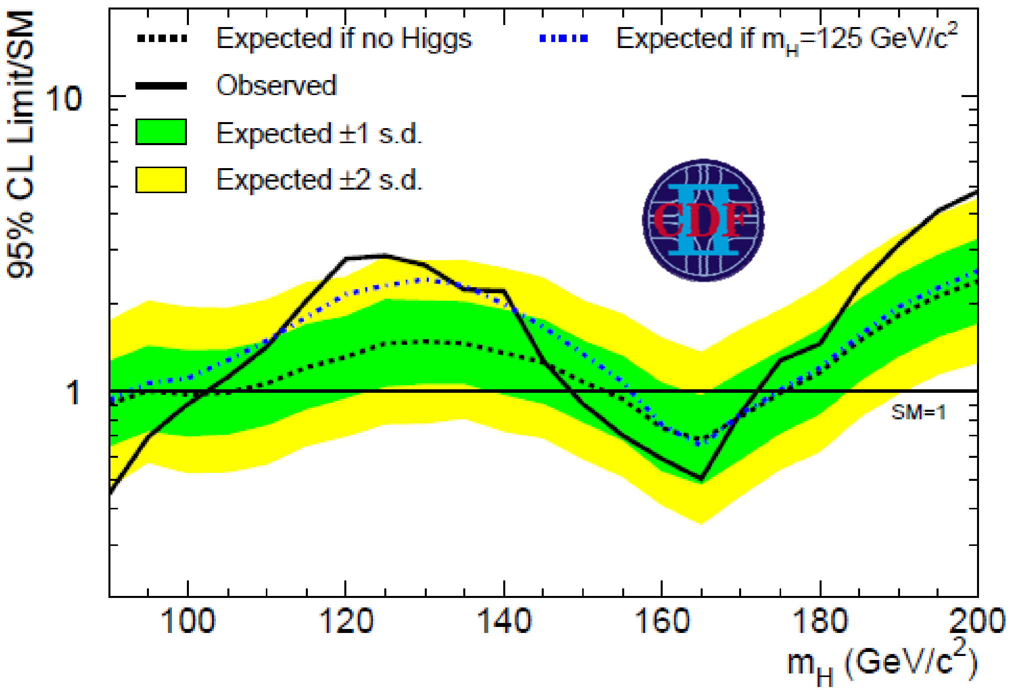


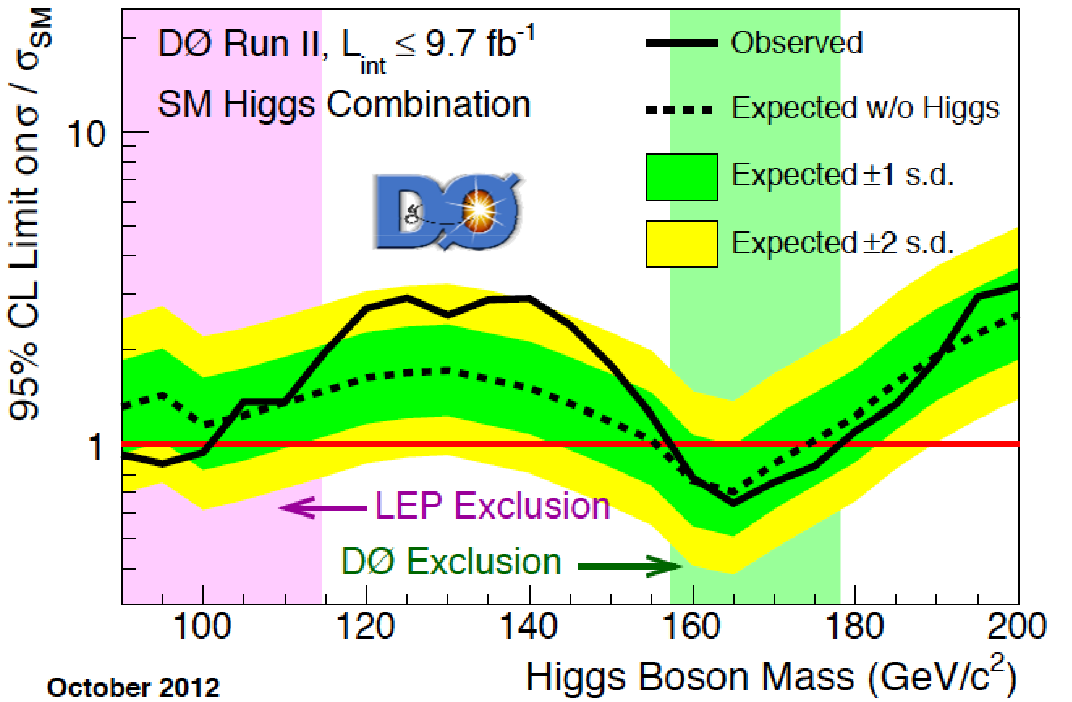
$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow b\bar{b}) = 0.19 \pm 0.09 \ (\text{stat} + \text{syst}) \ \text{pb}$$

SM Higgs @ 125 GeV: 0.12 ± 0.01 pb

CDF and D0 Combinations for all channels

CDF & D0 single-experiment combinations of all SM Higgs search channels($H \to WW$, $H \to bb$, $H \to \gamma\gamma$+ other)





October 2012

Remarkably similar shapes: excess <1 sigma below ~110 GeV,
broad excess around ~120-140 GeV,
exclusion around ~165 GeV

Observed 95% CL exclusion:

$90 < m_H < 102$ GeV, $152 < m_H < 172$ GeV

At m_H = 125 GeV:
Exp. limit: 1.46 x SM
Obs. limit: 2.89 x SM

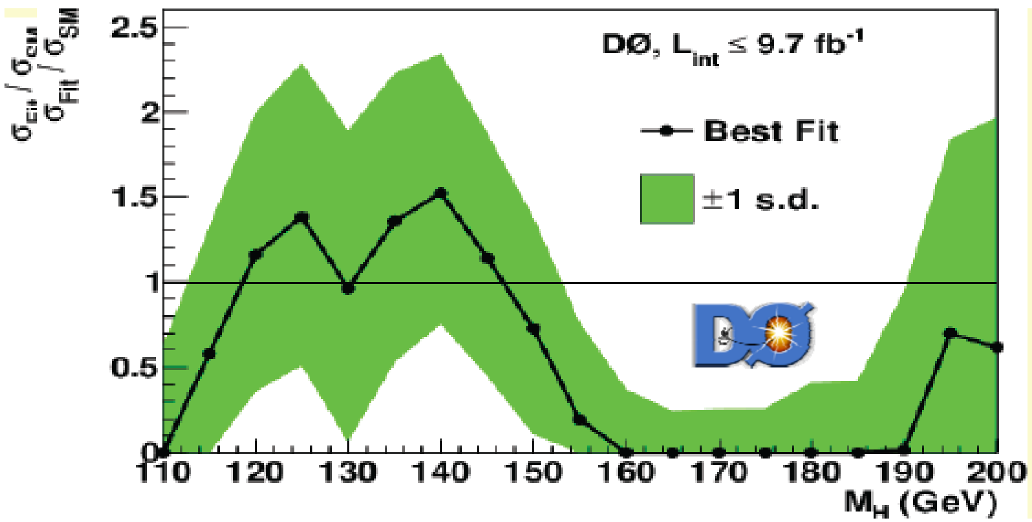
Observed 95% CL exclusion:

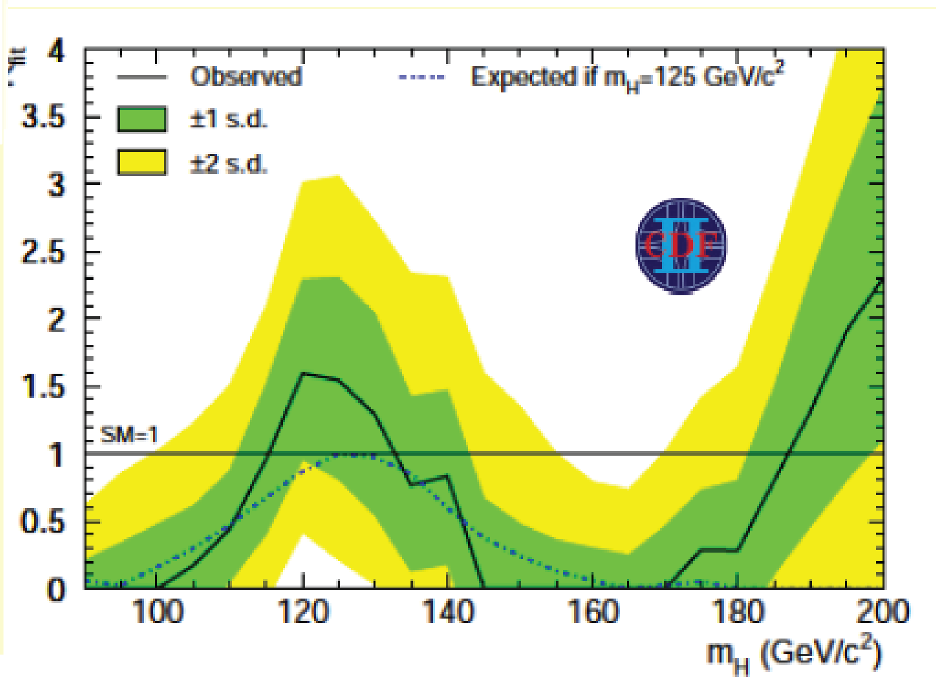
$90 < m_H < 101$ GeV, $157 < m_H < 178$ GeV

At m_H = 125 GeV:
Exp. limit: 1.66 x SM
Obs. limit: 2.92 x SM

Signal strenght: CDF and D0 combinations

For m_H @ 125 GeV



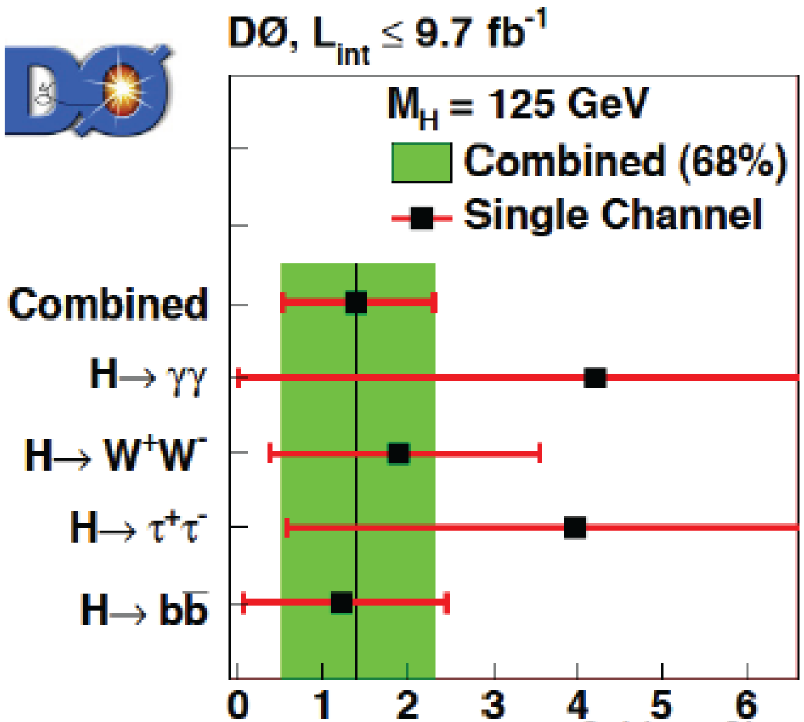


$1.40^{+0.92}_{-0.88}$

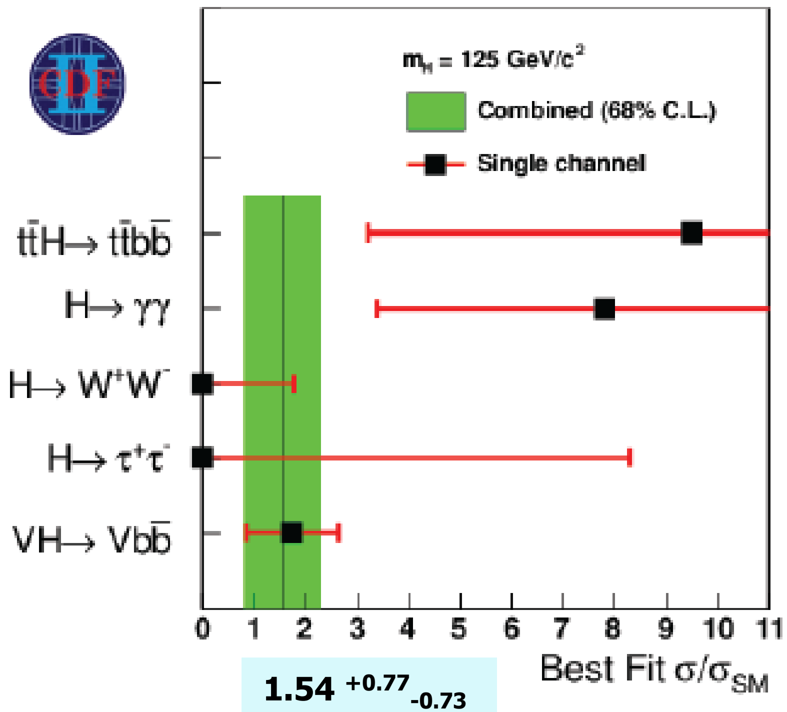
$1.54^{+0.77}_{-0.73}$

Signal strenght per channel

	DØ	CDF
Combination	$1.40^{+0.92}_{-0.88}$	$1.54^{+0.77}_{-0.73}$
$H \to \gamma\gamma$	$4.20^{+4.60}_{-4.20}$	$7.81^{+4.61}_{-4.42}$
$H \to \tau^+\tau^-$	$3.96^{+4.11}_{-4.38}$	$0.00^{+8.44}_{-0.00}$
$H \to W^+W^-$	$1.90^{+1.63}_{-1.52}$	$0.00^{+1.78}_{-0.00}$
$VH \to Vb\bar{b}$	$1.23^{+1.24}_{-1.17}$	$1.72^{+0.92}_{-0.87}$
$t\bar{t}H \to t\bar{t}b\bar{b}$	N/A	$9.49^{+6.60}_{-6.28}$

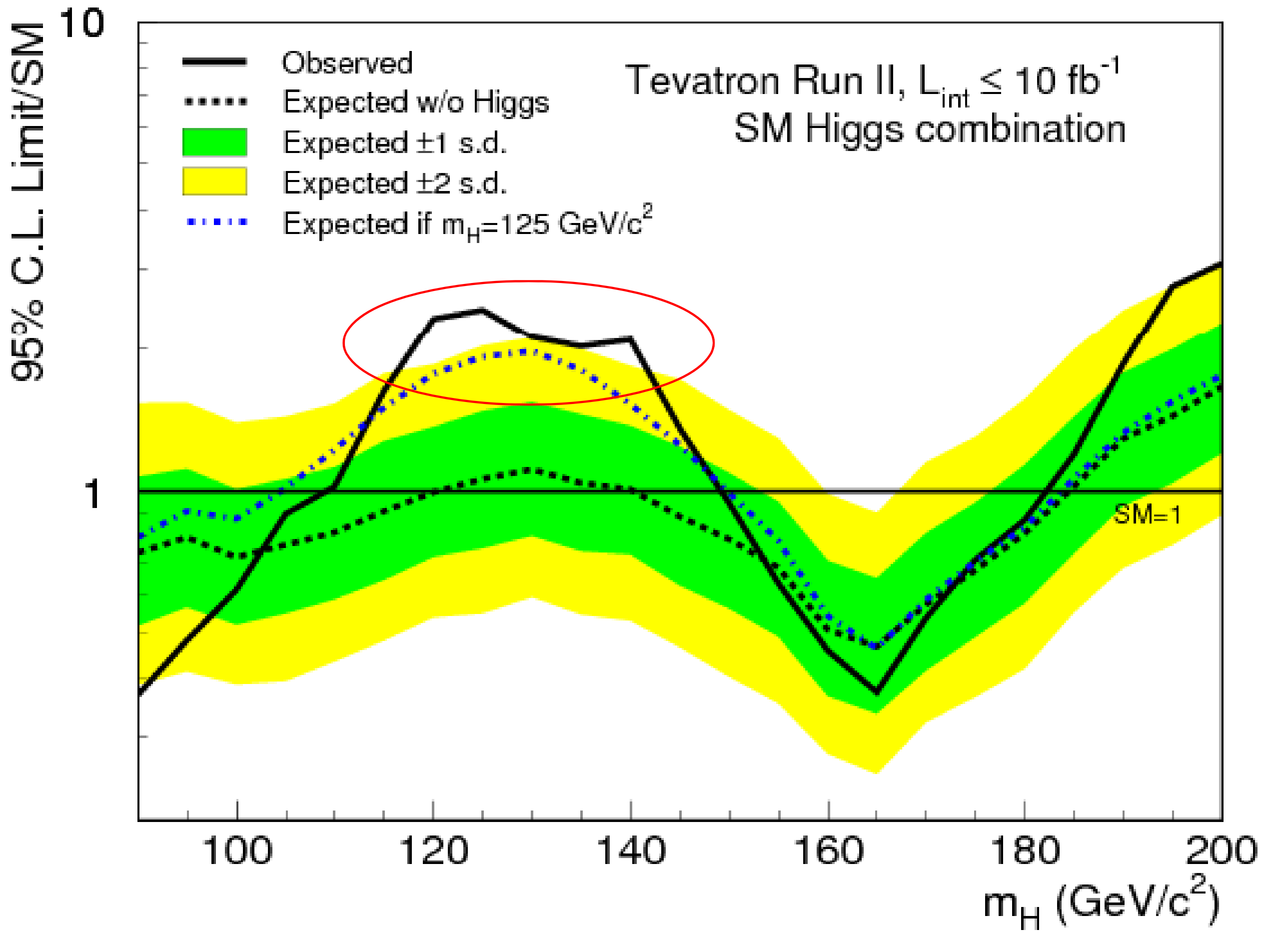


$1.40^{+0.92}_{-0.88}$



$1.54^{+0.77}_{-0.73}$

Full Tevatron combination

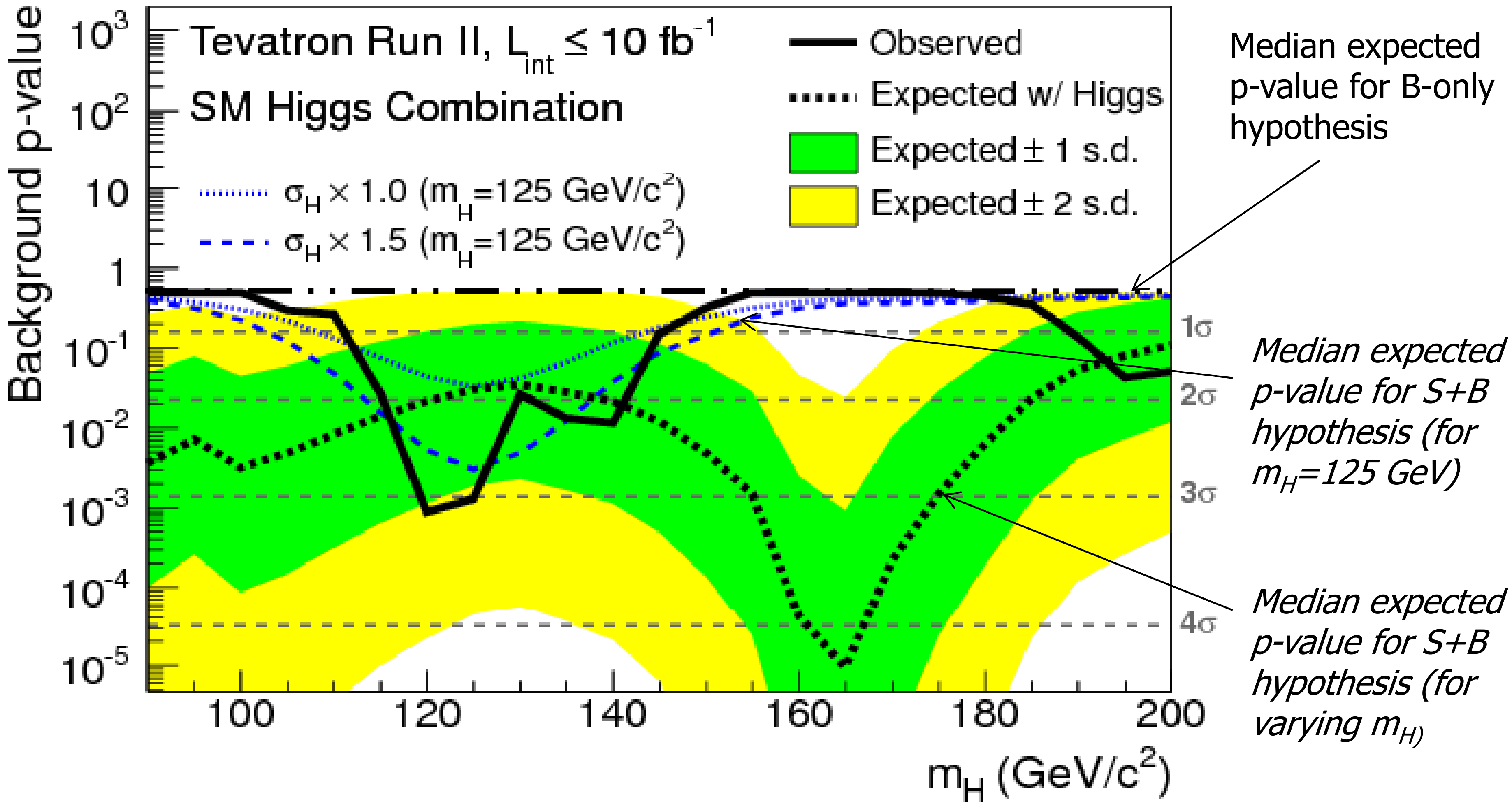


Significant excess, 2-3 sigma for 115→140 GeV

- Expected exclusion: 90 < m_H < 121 GeV, 140< m_H < 184 GeV
  Observed exclusion: 90 < m_H < 107 GeV, 149 < m_H < 182 GeV
- 95% CL limit at m_H=125 GeV: 1.09xSM (expected), 2.49xSM (observed)

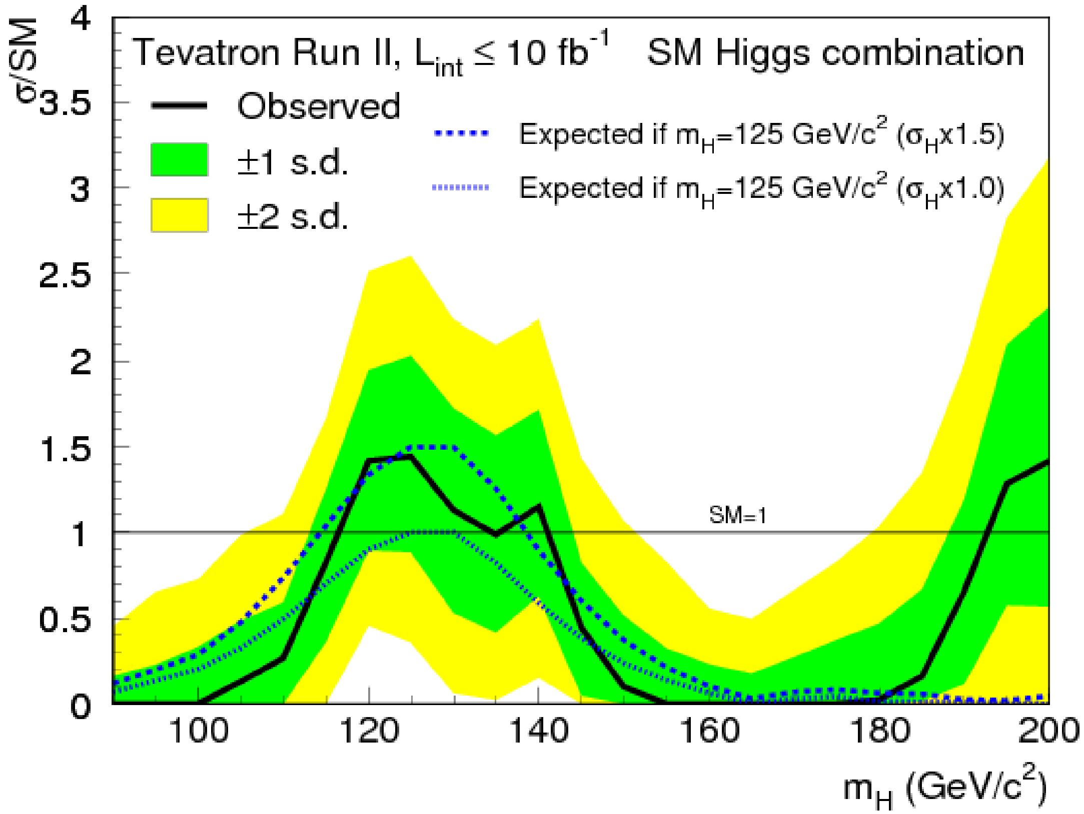
Quantifying the Excess: p-values

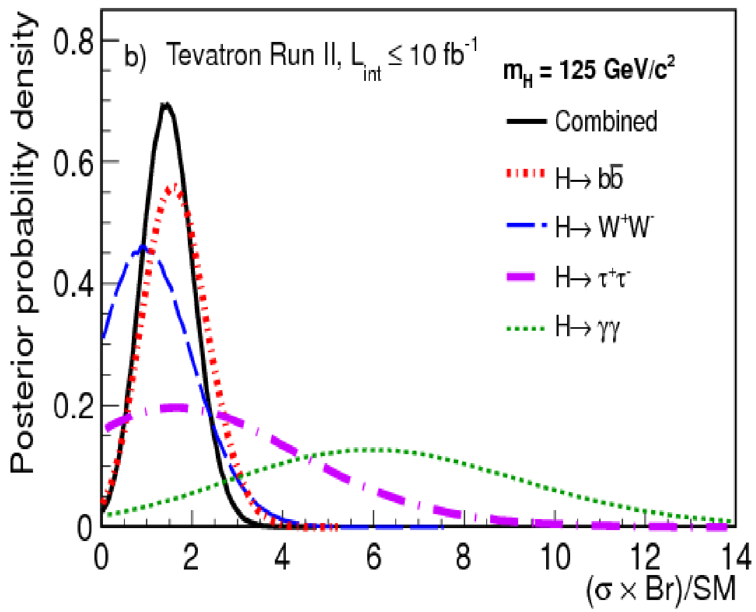
- Local p-value distribution for background-only hypothesis:

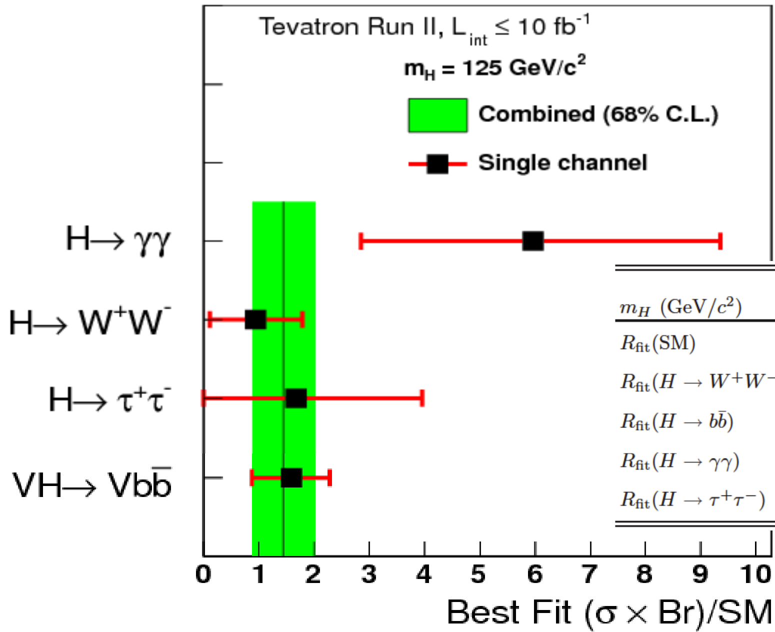


local p-value at m_H=125 GeV: 3.1σ (2.0σ expected)

Quantifying the signal: Best Fit Signal Rate







m_H (GeV/c^2)	125
R_{fit}(SM)	$1.44^{+0.59}_{-0.56}$
$R_{fit}(H \to W^+W^-)$	$0.94^{+0.85}_{-0.83}$
$R_{fit}(H \to b\bar{b})$	$1.59^{+0.69}_{-0.72}$
$R_{fit}(H \to \gamma\gamma)$	$5.97^{+3.39}_{-3.12}$
$R_{fit}(H \to \tau^+\tau^-)$	$1.68^{+2.28}_{-1.68}$

- Maximum likelihood fit to data with signal rate as free parameter.
- Best-fit signal rate at m_H=125 GeV:

$$\sigma_{fit} / \sigma_{SM} = 1.44 \pm 0.59$$

Consistent with SM Higgs.

Reasonably consistent across channels.

Probing Higgs Boson Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (arXiv:1209.0040).
  Basic assumptions:
  - there is only one underlying state at m_H~125 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).

  Additional assumption made in this study:
  - no additional invisible or undetected Higgs decay modes.
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$$

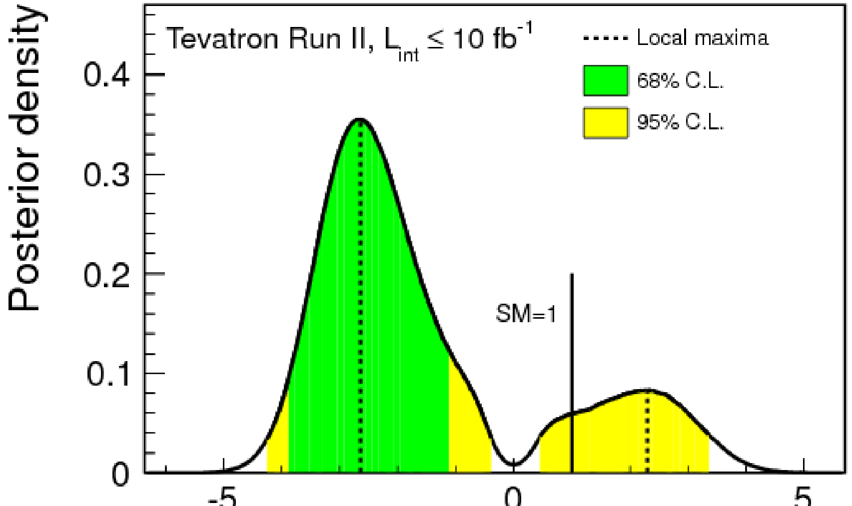
$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, M_H)$$

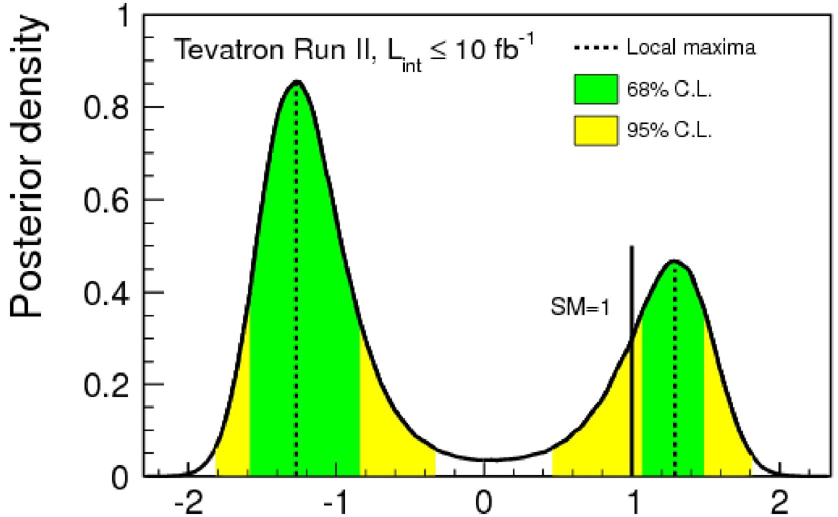
$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, M_H)$$

Probing Higgs Boson Couplings: Benchmark I

- Simplest scenario of measuring one coupling deviation at a time assuming SM values for the others.



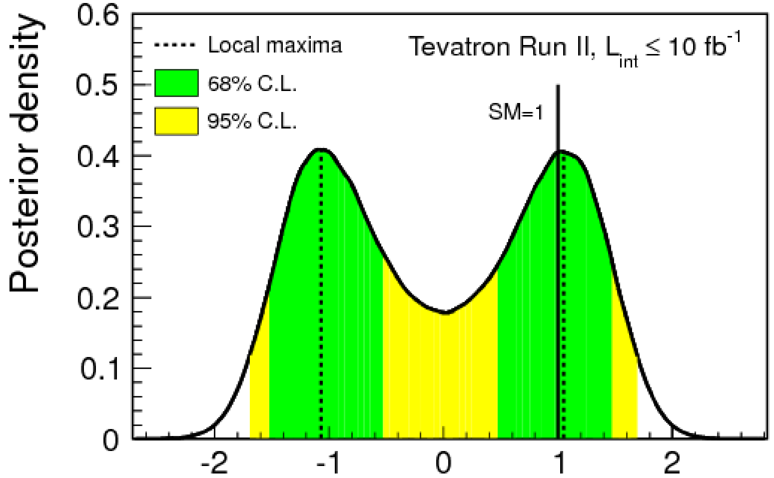
Best fit: $\kappa_f = -2.64$



Best fit: $\kappa_W = -1.27$

- Preference for negative value for $\kappa_W(\kappa_f)$ when $\kappa_f=1(\kappa_W=1)$ due to excess in $H \rightarrow \gamma\gamma$

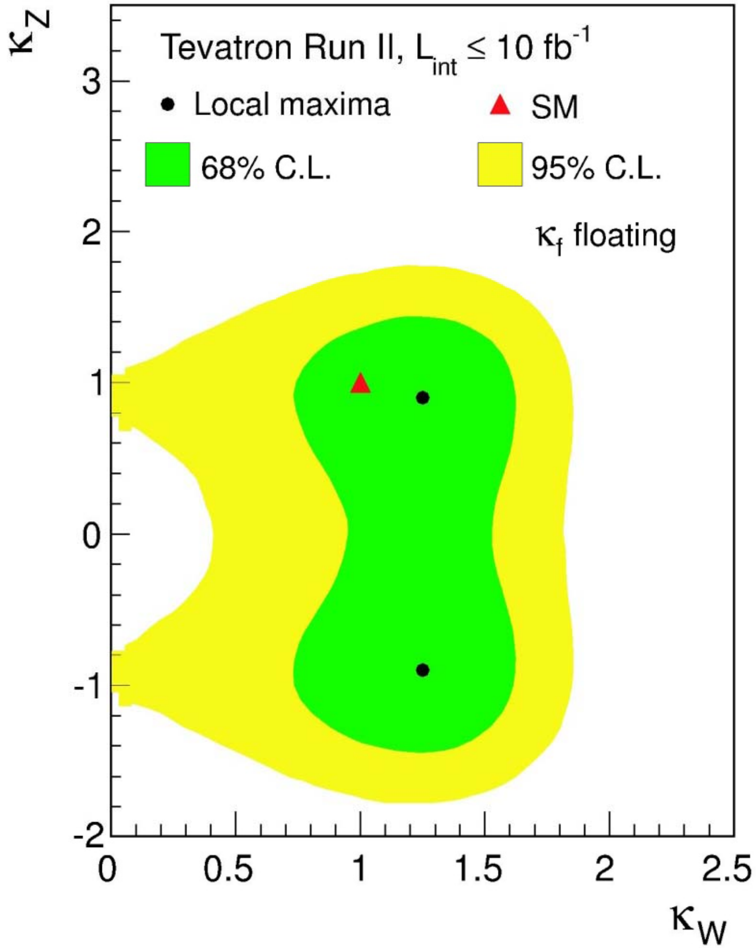
- Sensitivity to κ_Z mainly though $ZH \rightarrow llbb$, $\nu\nu bb$ channels → posterior density is nearly symmetric
  - Best fit: $\kappa_Z = \pm 1.05$



Probing Higgs Boson Couplings: Benchmark II

- Both κ_W and κ_Z vary independently
  - κ_f integrated over
  - Best fit: $(\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$

- The point $(\kappa_W, \kappa_Z) = (0, 0)$ corresponds to NO Higgs boson production or decay in the most sensitive search modes at the Tevatron and is not included within the 95% C.L. region due to the significant excess of events in the SM Higgs boson searches @ 125 GeV

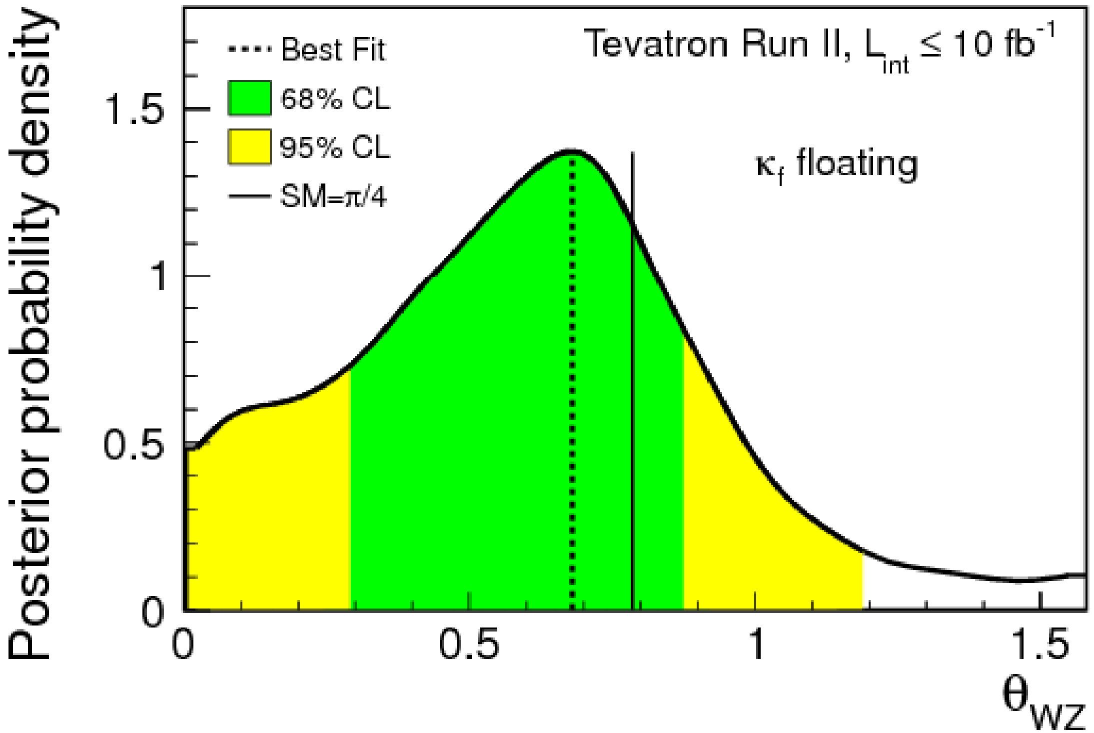


Probing Higgs Boson Couplings: Benchmark II

Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$

- Measure $\theta_{WZ} = \tan^{-1}(\kappa_Z/\kappa_W) = \tan^{-1}(1/\lambda_{WZ})$

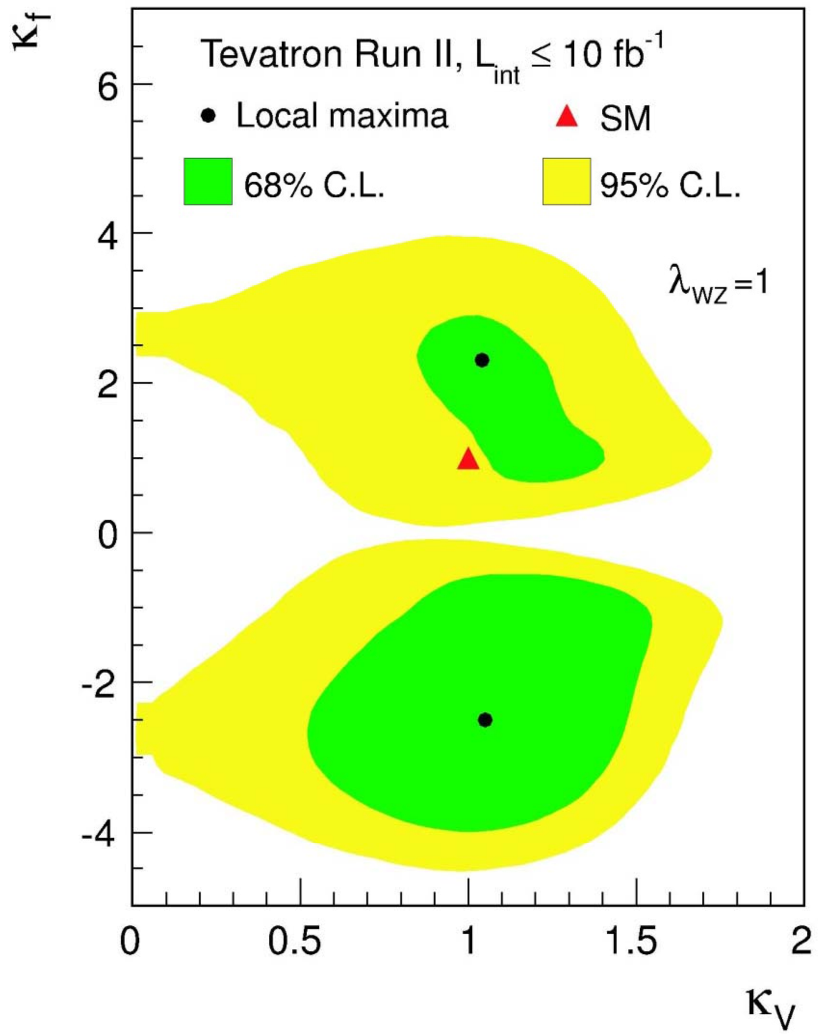
$$\theta_{WZ} = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$



Probing Higgs Boson Couplings: Benchmark III

- Measure simultaneously κ_V and κ_f (assuming λ_{WZ}=1).

- Asymmetry is from the excesses in the $H \rightarrow \gamma\gamma$
- Two minima:
  $(\kappa_V, \kappa_f)=(1.05,-2.40)$ and
  $(\kappa_V, \kappa_f) = (1.05, 2.30)$
- The integral of the posterior density in the (+,+) quadrant is 26% of the total, while the remaining 74% of the integral of the posterior density is contained within the (+,–) quadrant



Summary and Outlook

- Latest Tevatron results based on full Run II dataset in all major search channels are now submitted to PRD.

- Previously published evidence for WX/ZX production with X→bb, where X is consistent with a SM Higgs boson of 125 GeV, as the newly discovered particle by ATLAS & CMS is so far the only evidence for fermionic decays of the Higgs

- The H→bb channel is unlikely to be seen at the 5 sigma level before the 2015 LHC Run, except maybe through combination of all results available.

- Combining all channels, Tevatron has achieved 95%CL SM sensitivity over almost all the foreseen accessible mass range (90 – 185 GeV), a good performance given the intergrated Luminosity and center of mass energy.

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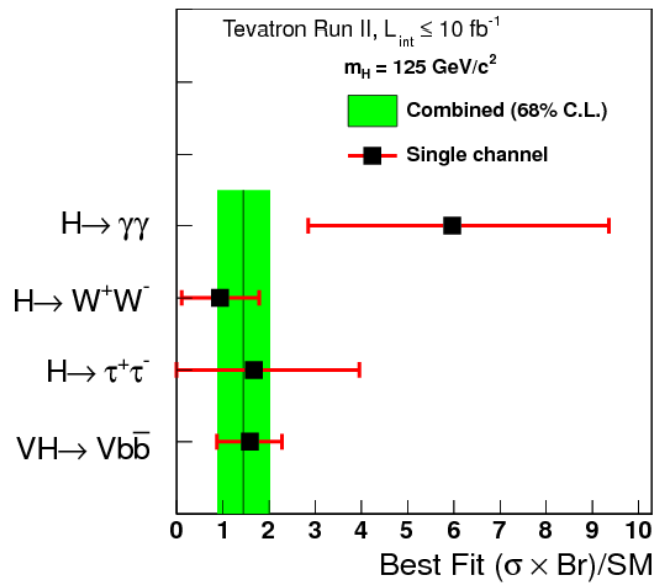
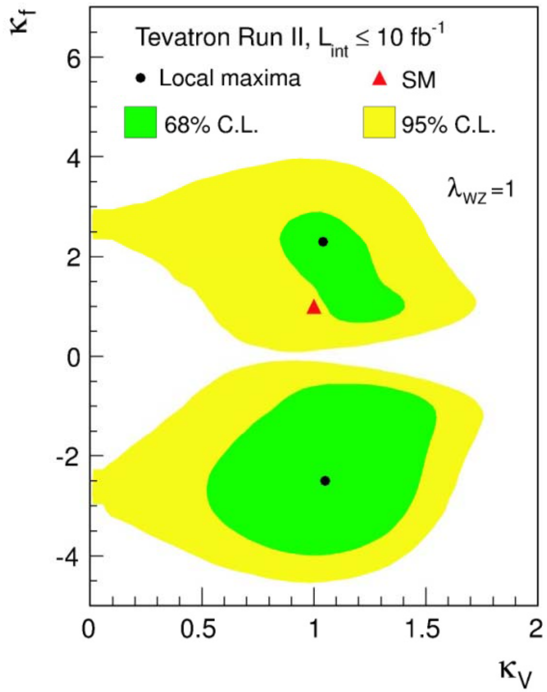
- Signal strenghts in 4 decay channels, and results on Higgs couplings to fermions, W & Z, are consistent with the SM.

- Despite the impressive progress on Higgs physics at LHC, the Tevatron has still some valuable information to provide (spin-parity results under preparation, targetting LHCP).

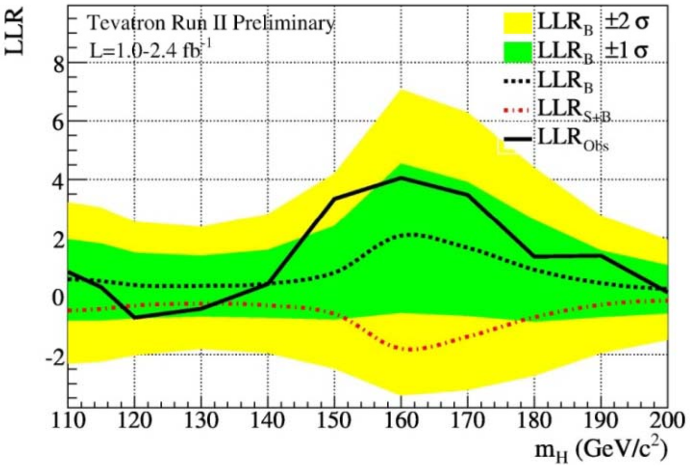




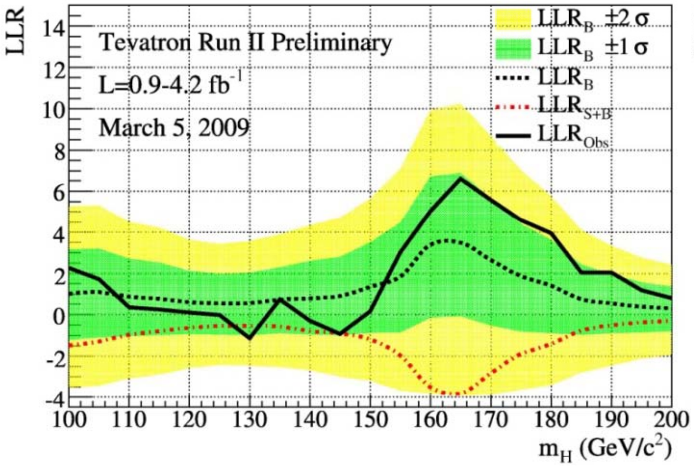
Backup Slides

history of Tevatron results

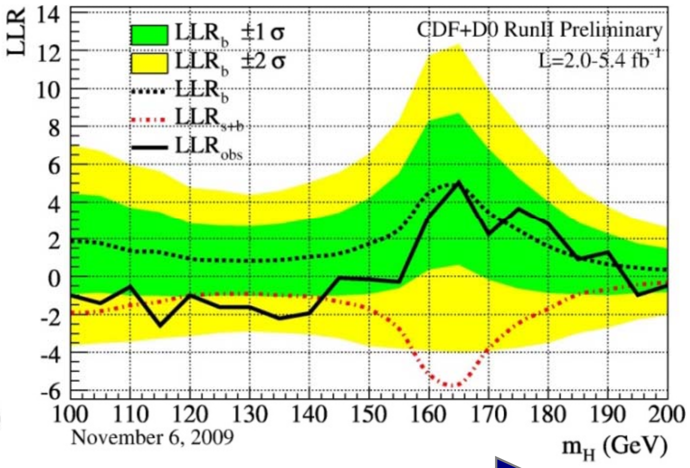
Data of 2007; up to 2.4 fb^{-1}



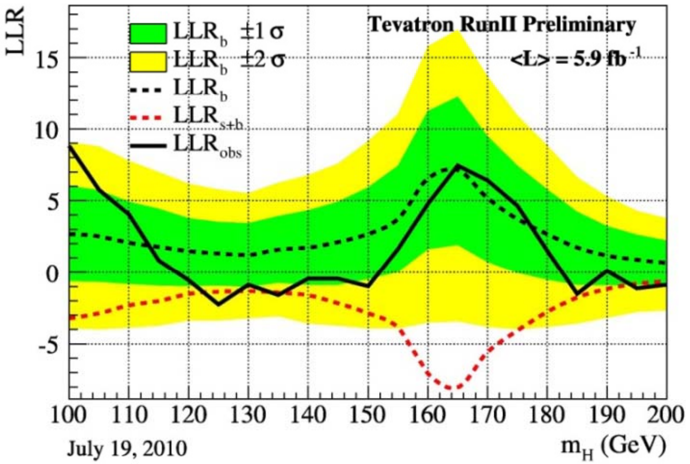
Data of 2008; up to 4.2 fb^{-1}



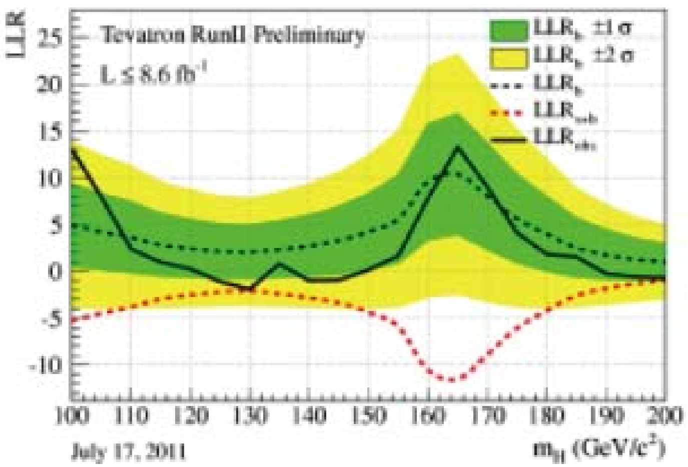
Data of mid 2009; up to 5.4 fb^{-1}



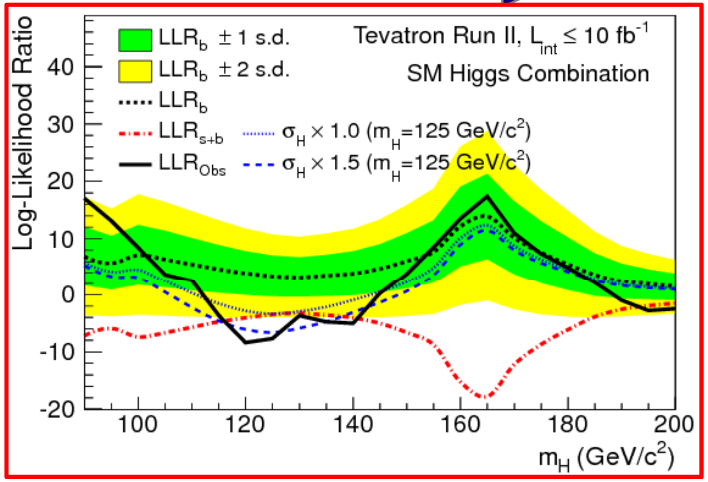
Time



Data of mid 2010; up to 5.9 fb^{-1}



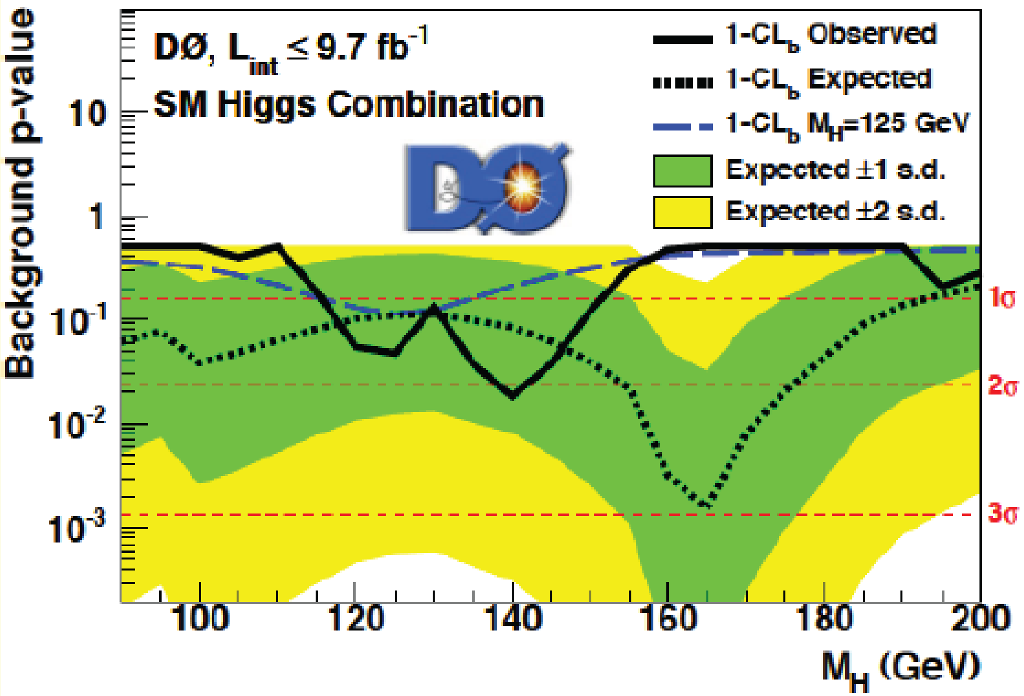
Data of mid 2011; up to 8.6 fb^{-1}

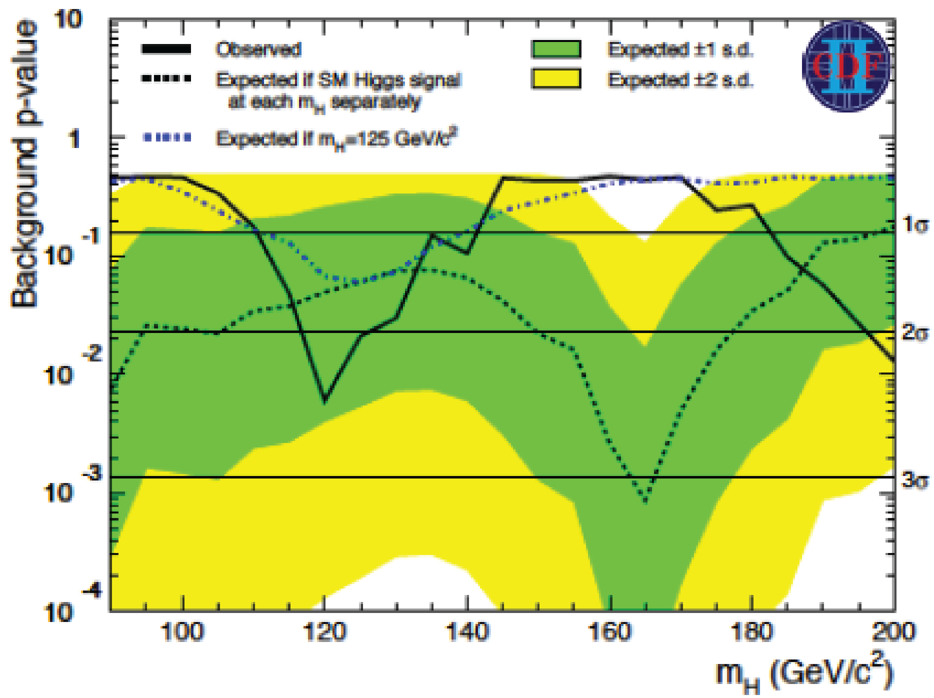


Full data set; up to 10 fb^{-1}

CDF and D0 Combinations : P-values

- p-value for background hypothesis provides information about the consistency with the observed data
- Local p-value distribution for background only expectation:
  - D0: 1.7 s.d. (@125 GeV)
  - CDF: 2.0 s.d. (@125 GeV)





Probing Higgs Boson Couplings

$$\sigma(gg \to H) = \sigma_{SM}(gg \to H)(0.95\kappa_f^2 + 0.05\kappa_f\kappa_V)$$
$$\sigma(VH, VBF) = \sigma_{SM}(VH, VBF)\kappa_V^2$$

$$\Gamma(H \to VV) = \Gamma(H \to VV)_{SM}\kappa_V^2; (V = W, Z)$$

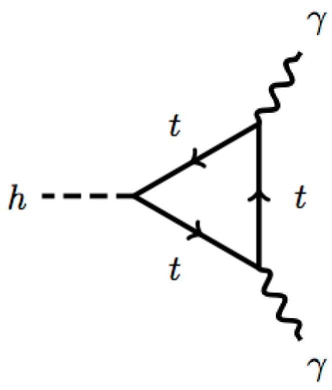
$$\Gamma(H \to ff) = \Gamma(H \to ff)_{SM}\kappa_f^2$$

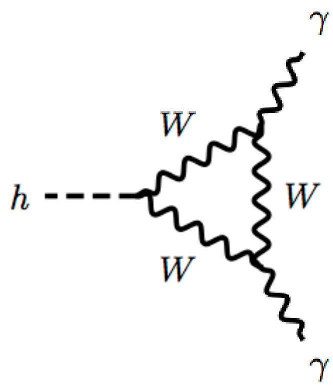
$$\Gamma(H \to gg) = \Gamma(H \to gg)_{SM}(0.95\kappa_f^2 + 0.05\kappa_f\kappa_V)$$

$$\Gamma(H \to \gamma\gamma) = \Gamma(H \to \gamma\gamma)_{SM}|\alpha\kappa_V + \beta\kappa_f|^2$$

$$\mathcal{BR}(H \to XX) = \frac{\Gamma(H \to XX)}{\Gamma_{TOT}}$$

α=1.28; β=-0.21;
from Spira et al. arXiv:hep-ph/9504378
=> $H\to\gamma\gamma$ from destructive interference between the two contributions
- If any of the couplings is negative, interference becomes constructive
=> Larger rate of the $H \to\gamma\gamma$





Summary on couplings

- **Couplings to fermions:** $\kappa_f = -2.64^{+1.59}_{-1.30}$
- **Couplings to bosons:**

$$\kappa_W = -1.27^{+0.46}_{-0.29}\,;\, \textit{second interval}\; 1.04 < \kappa_W < 1.51$$

$$\kappa_Z = \pm 1.05^{+0.45}_{-0.55}$$

- if varied together: **(κ_W, κ_Z) = (1.25,±0.90)**

- **For custodial symmetry:**

$$\theta_{WZ} = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$

- **If custodial symmetry is preserved:**
  (κ_V, κ_f)=(1.05,−2.40) and (κ_V, κ_f) = (1.05, 2.30)