SM Higgs boson studies at the Tevatron

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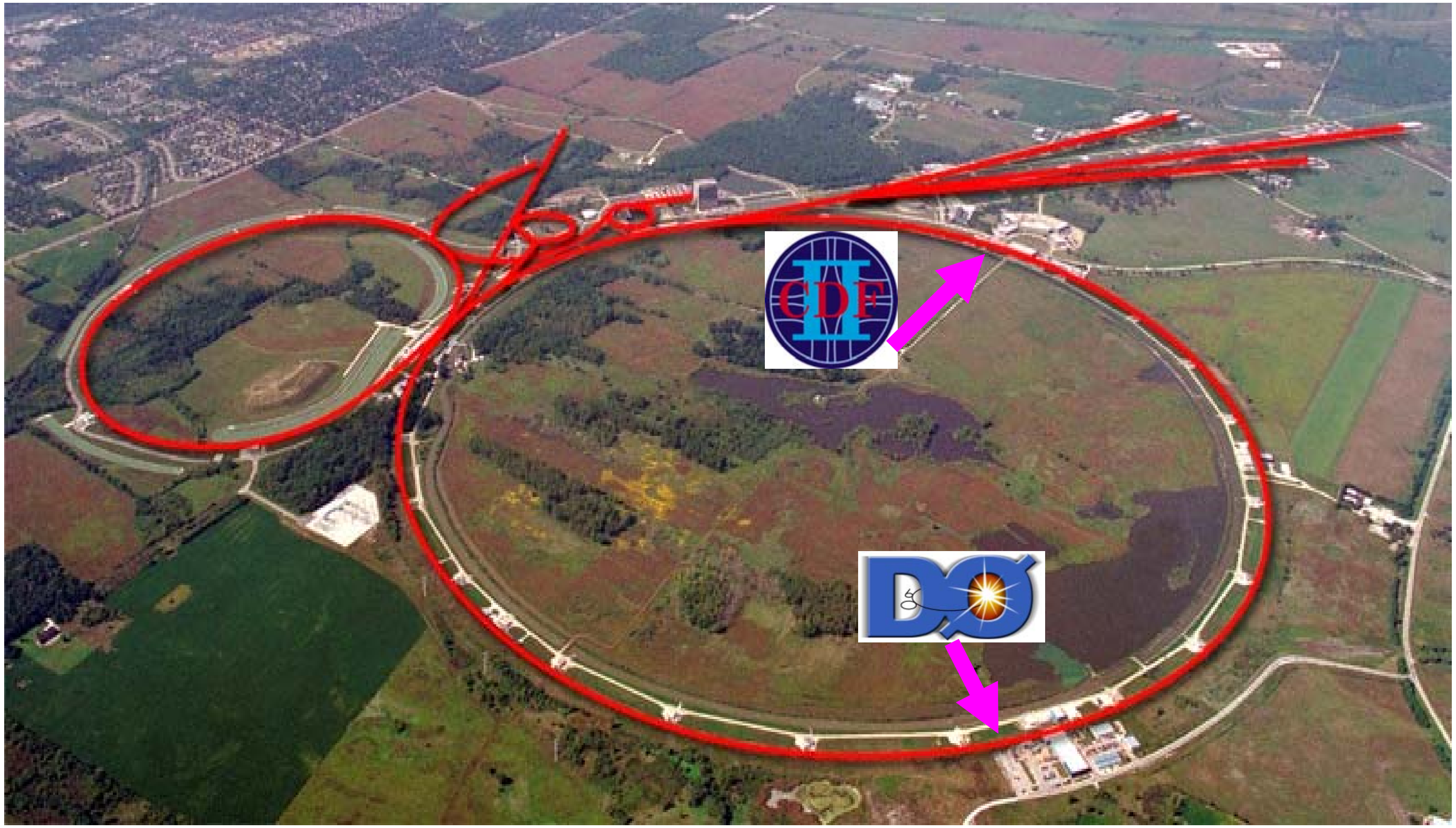
On behalf of CDF and Dzero

IHEP conference, June 7, 2013

Thanks to all CDF & DZero colleagues,

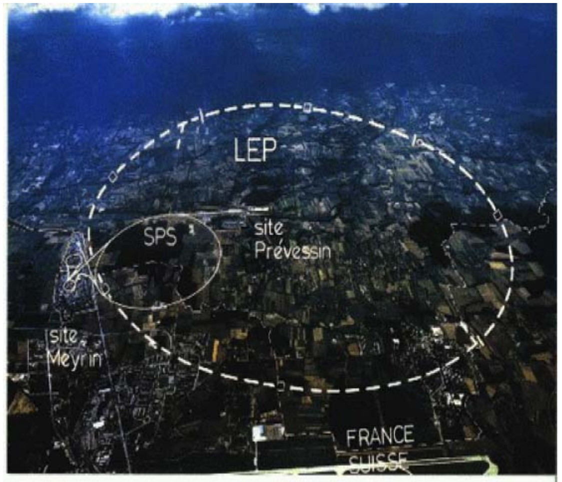


Outline

- 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)

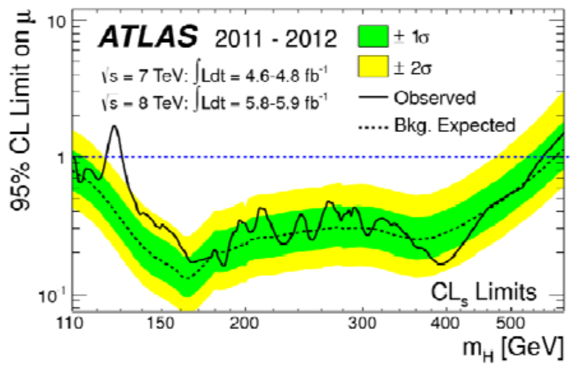


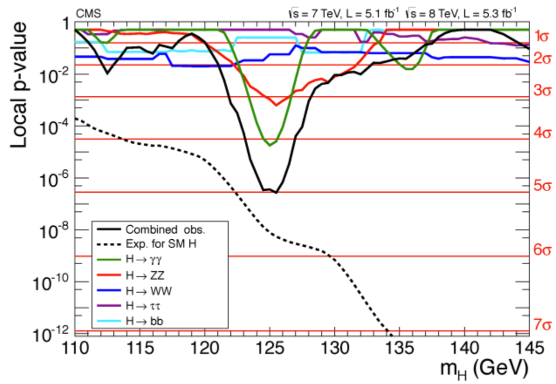
- **LEP (1989 - 2000): m_H > 114.4 GeV@95% CL**

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 (2011 - 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)

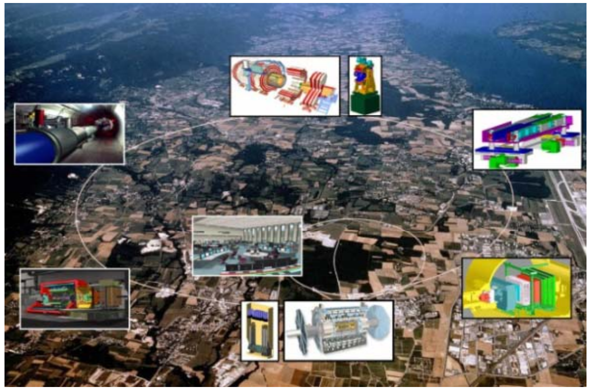


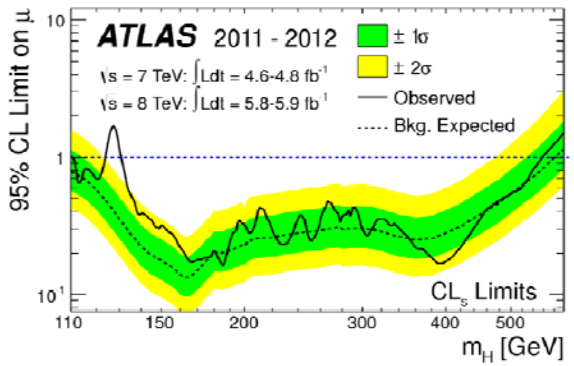


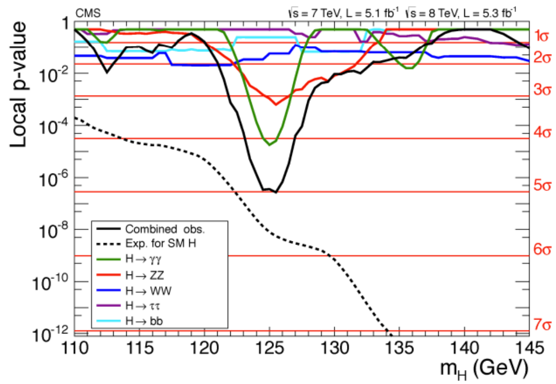
Higgs: Historical perspective and current Status

- **Tevatron Run II (2002 – 2011, 2 TeV):**
  - 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 (2011 – 2012, 7 - 8 TeV):**
  - 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)**







- **LHC ("full 2011-2012 dataset"):**
  - 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→ττ (full stat) but low ATLAS signal (1.1σ, 1.7σ expected, 18fb^{-1})

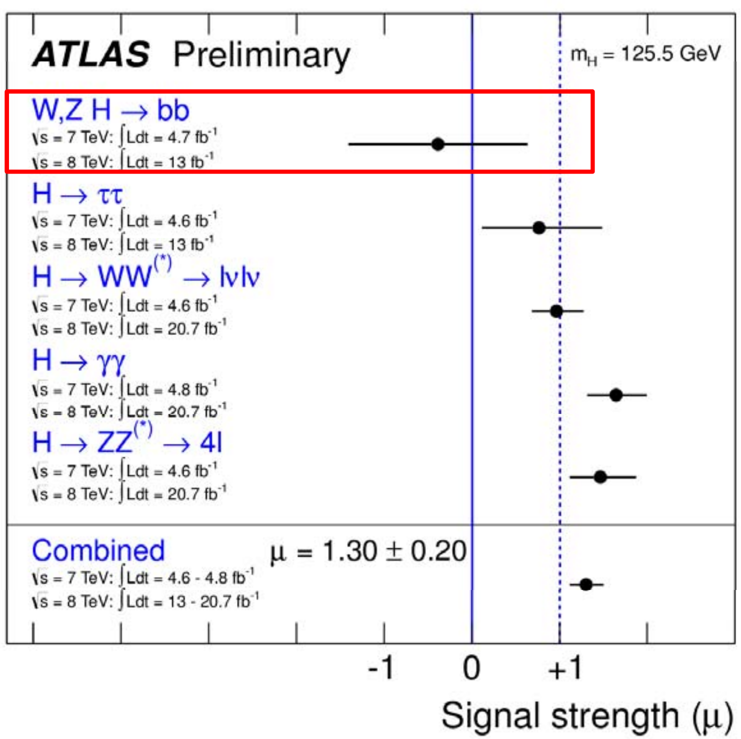
  → **While it "is" a Higgs boson, the fermionic decays are not yet firmly established.**

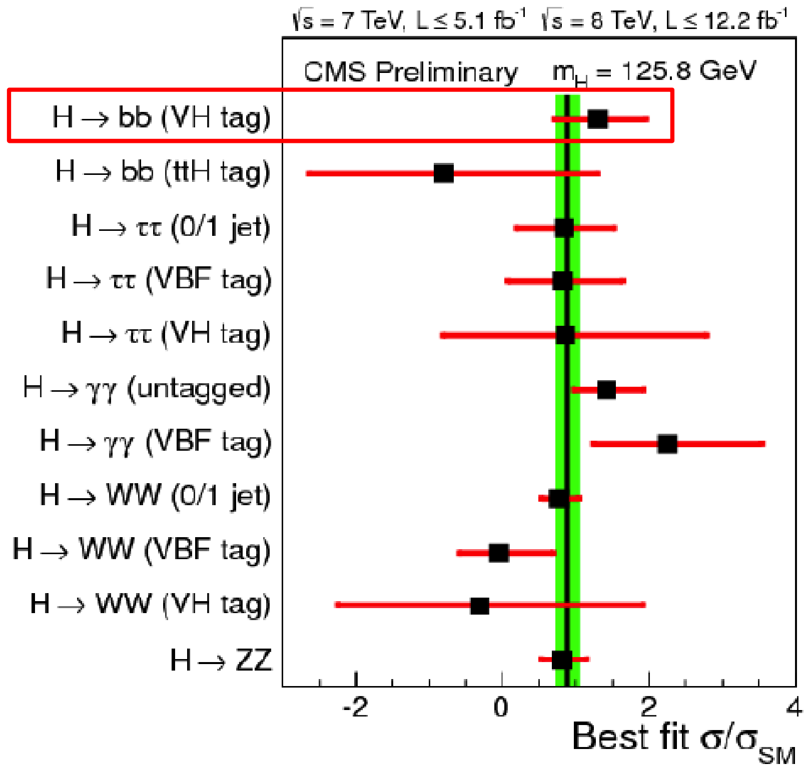
Current situation

- **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. With 23 fb^{-1} ~2.1 σ excess at CMS
  - strong indications (2.9 σ)of fermionic decays at LHC from CMS H→ττ(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.



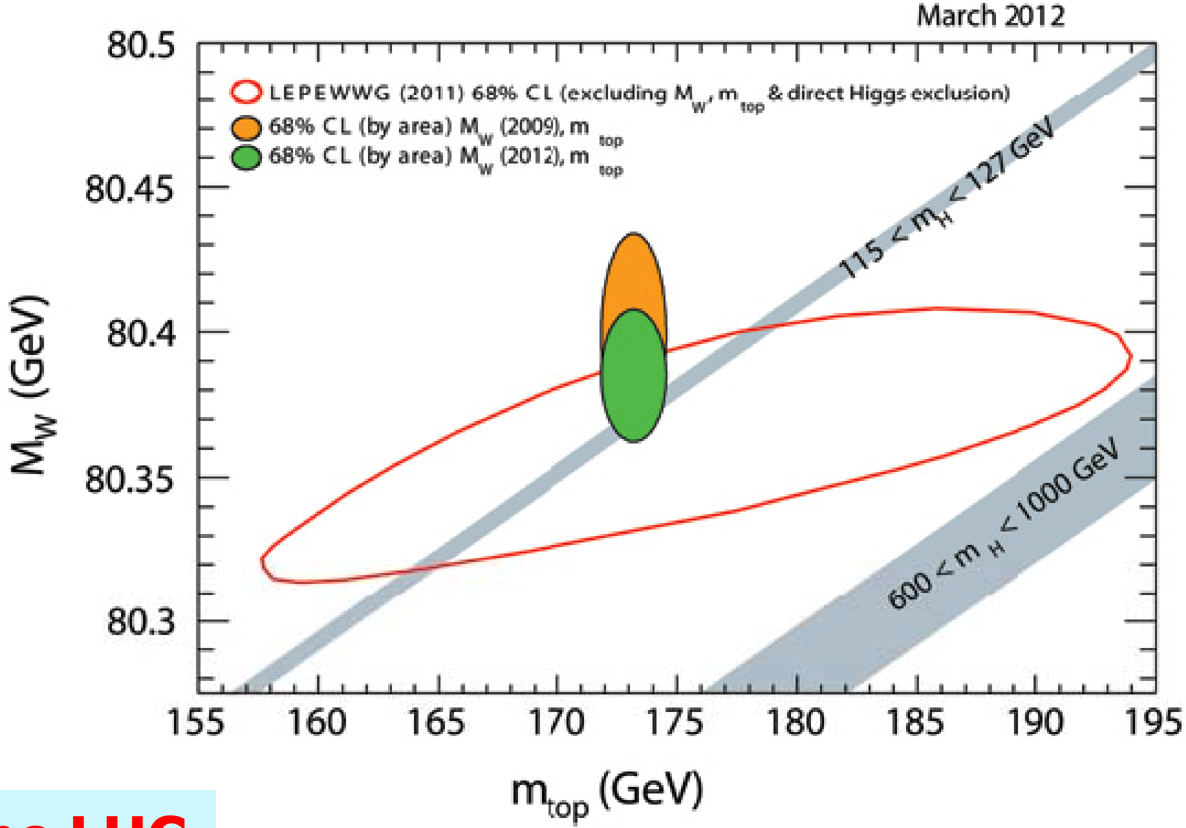


Recently updated top quark and W boson mass measurements from the Tevatron

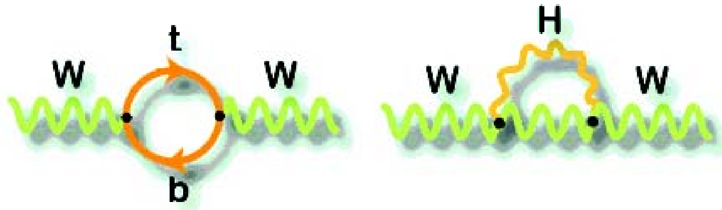
$m_W = 80385 \pm 15$ MeV

$m_t = 173.2 \pm 0.9$ 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



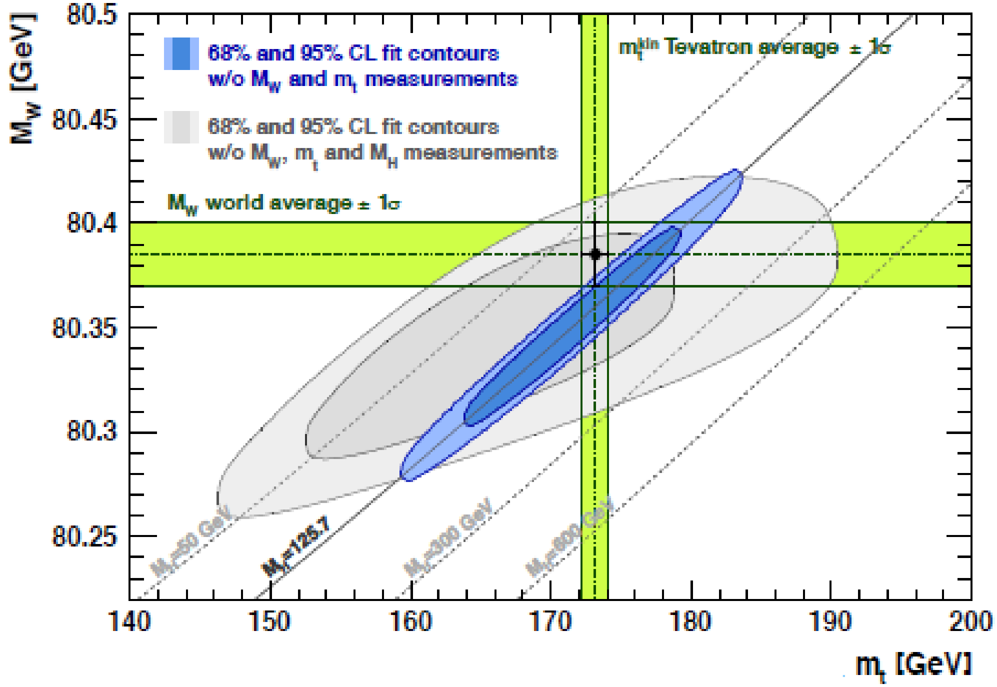
W-mass : how far can we go?

If we use the measured mass of the Higgs-like boson to constrain the W boson mass based on SM, we get:

$m_W = 80.359 \pm 0.011$ GeV

Comparing with the current world average directly measured value:

$m_W = 80.385 \pm 0.015$ GeV



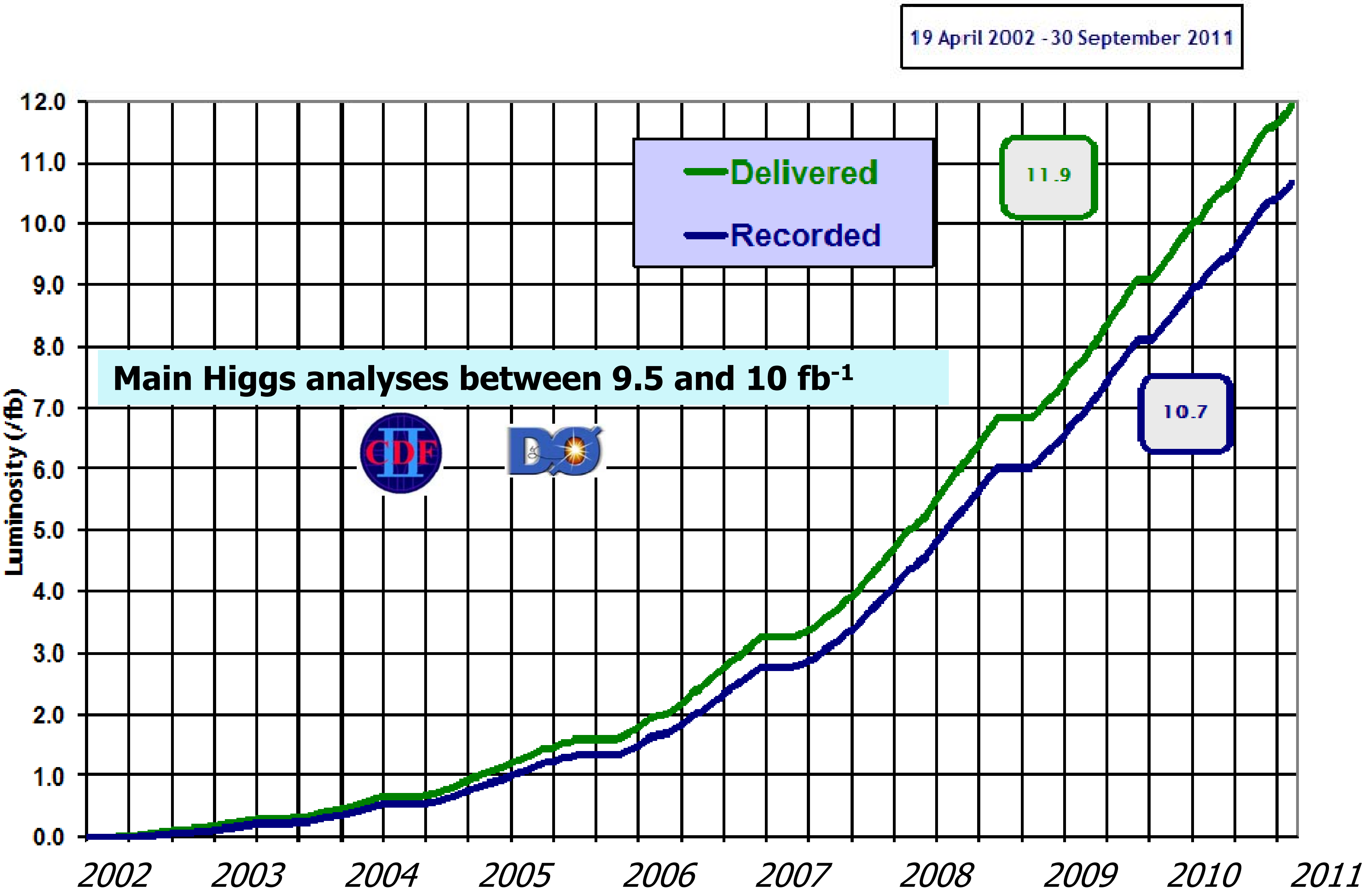
With a world average around 10 MeV dominated by the Tevatron, and no change in central values, test direct and indirect Higgs mass values.

Significant anomaly could be detected if central value would slightly move apart, while reducing uncertainties .

Currently we have good agreement !!!

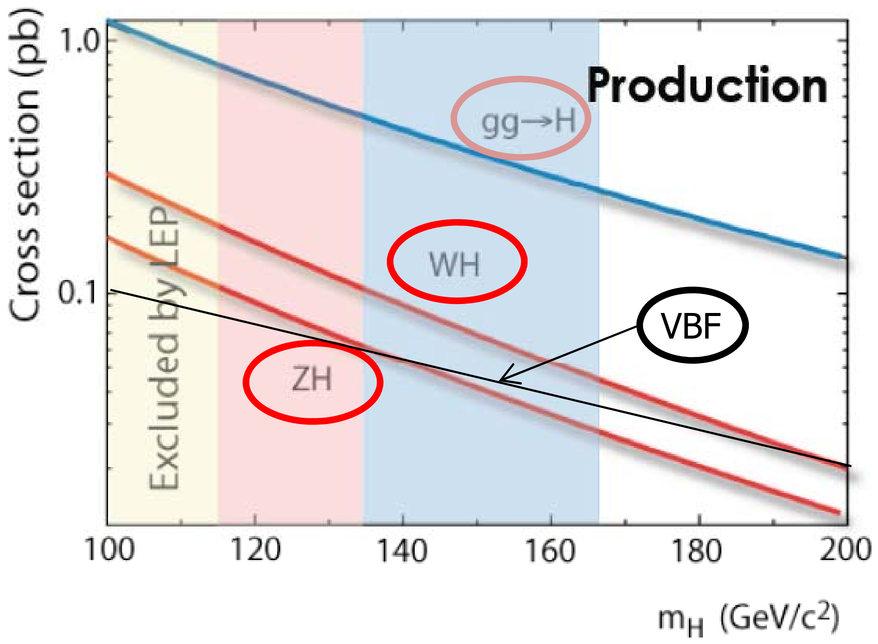
test SM consistency via m_W m_{top} m_{Higgs} at > 2 sigma level

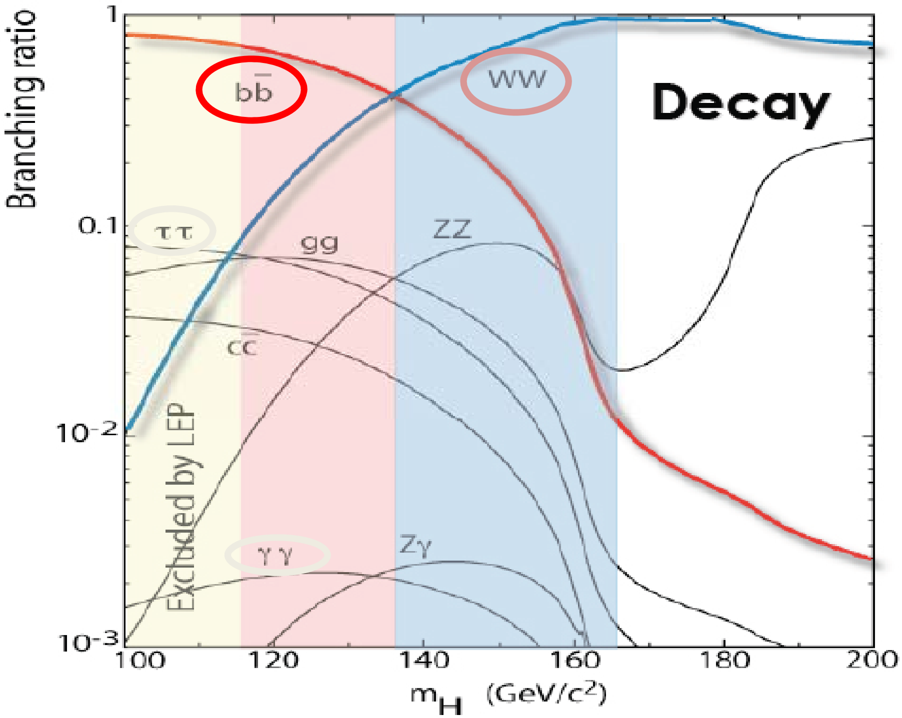
Tevatron Luminosity



Thanks to the Tevatron Accelerator Group for such a performance!

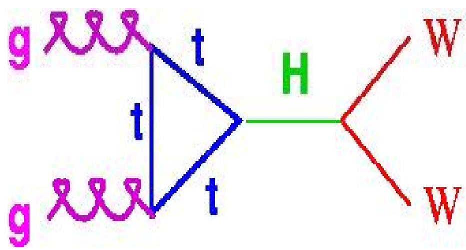
Higgs Production and Decay at the Tevatron





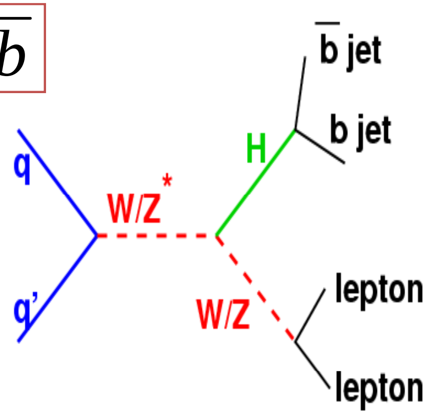
"High" mass (m_H > 135 GeV) dominant decay:

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



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

Final Higgs combination from Tevatron

Combination: arXiv:hep-ex/1303.63416; submitted to Phys. Rev. D

All SM channels searched

Full luminosity used in almost all channels

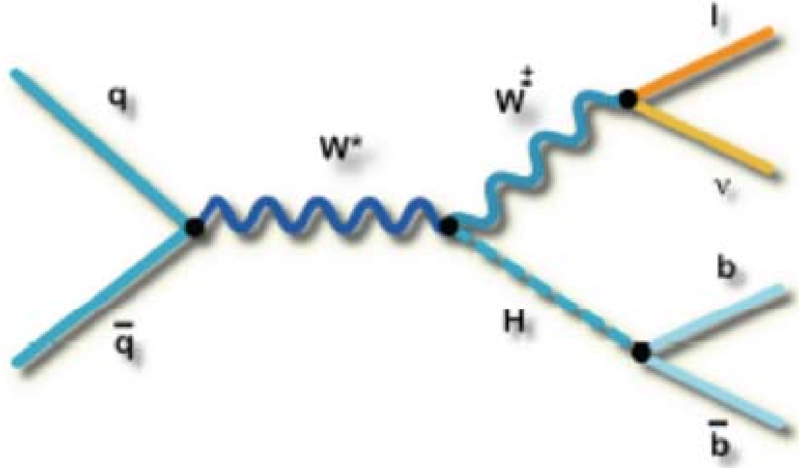
CDF

Channel			Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels	4×(5 b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels	3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$	(3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels	2×(4 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels	2×(4 b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$	(2 b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$	(4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45	100-150
$H \to W^+W^-$	2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)	$H \to W^+W^-$	9.7	110–200
$H \to W^+W^-$	(e-τ_{had})+(μ-τ_{had})		9.7	130–200
$WH \to WW^+W^-$	(same-sign leptons)+(tri-leptons)		9.7	110–200
$WH \to WW^+W^-$	(tri-leptons with 1 τ_{had})		9.7	130–200
$ZH \to ZW^+W^-$	(tri-leptons with 1 jet,≥2 jets)		9.7	110–200
$H \to \tau^+\tau^-$	(1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$	1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$	(four leptons)	$H \to ZZ$	9.7	120–200

DØ

Channel			Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$	(4 b-tag categories)×(2 jets, 3 jets)	$H \to b\bar{b}$	9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$	(2 b-tag categories)		9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$	(2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	(0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{had}\nu$			7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$	(2 b-tag categories)×(2 jets, 3 jets)		9.7	100–200
$VH \to e^\pm\mu^\pm + X$			9.7	100–200
$VH \to \ell\ell\ell + X$			9.7	100–200
$VH \to \ell\bar{\nu}jjjj$	(≥4 jets)		9.7	100-200
$VH \to \tau_{had}\tau_{had}\mu + X$		$H \to \tau^+\tau^-$	8.6	100–150
$H+X \to \ell^\pm\tau^\mp_{had}jj$			9.7	105–150
$H \to \gamma\gamma$			9.6	100-150

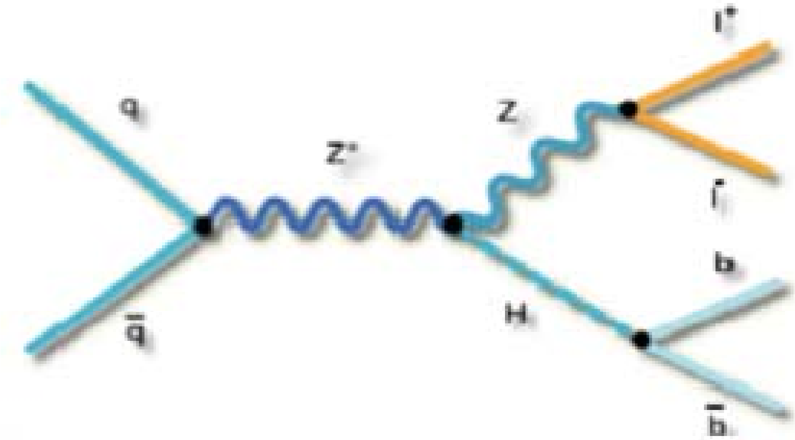
Low Mass Higgs Channels



WH→lνbb: MET+l+bb

Large production cross section

Higher backgrounds than in ZH→llbb

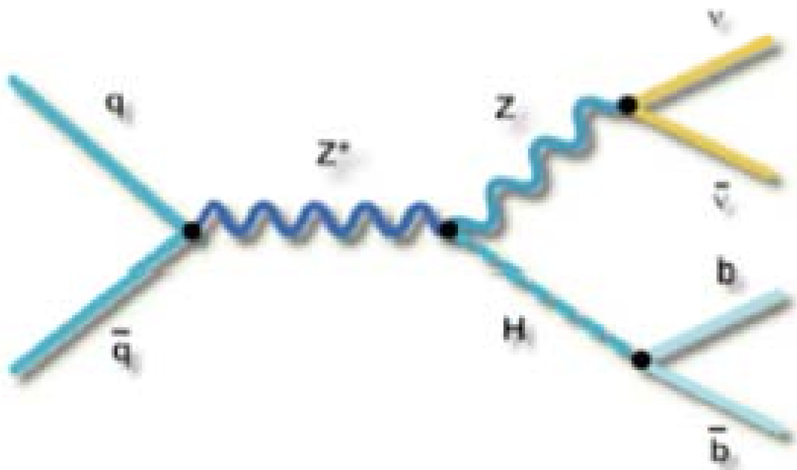


ZH→llbb: ll+bb

Low background

Fully constrained

Small Signal



ZH→ννbb: MET+bb

signal 3x larger than ZH→llbb

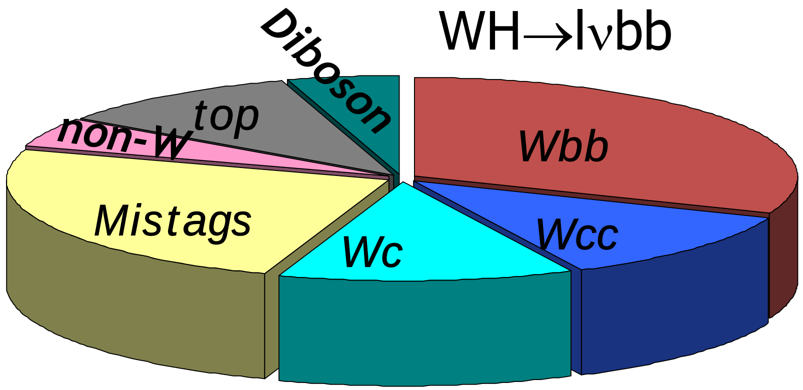
(+ contributions from WH)

difficult backgrounds

Low Mass Higgs Searches

Increase lepton reconstruction and selection efficiencies

Understand background



Specific to low mass analyses:

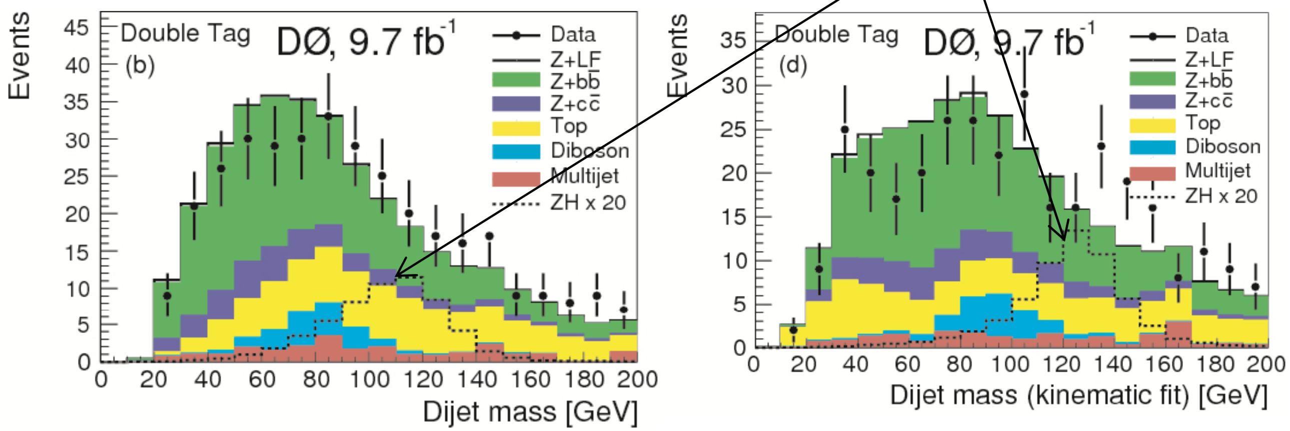
B-tagging (next slide)

Optimize dijet mass resolution

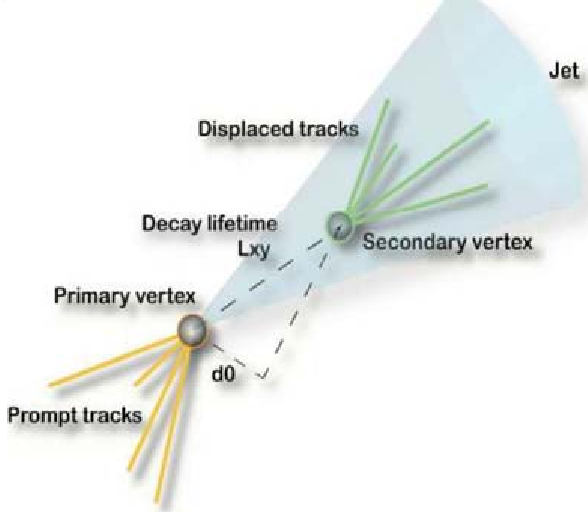
➔ needs precise calibration and resolution for gluon and quark jets separately

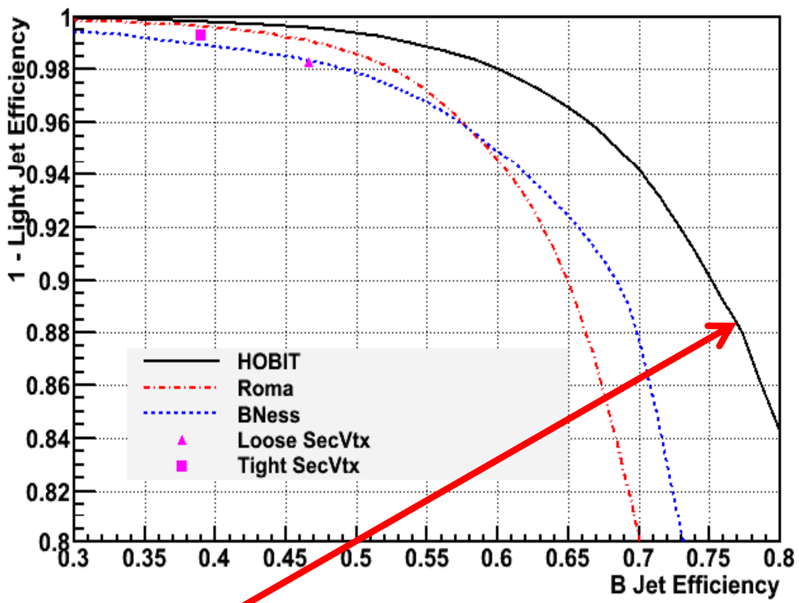
➔ new techniques still explorec (NN, tracks + calorimeter cells)

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



Low Mass Higgs Searches





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

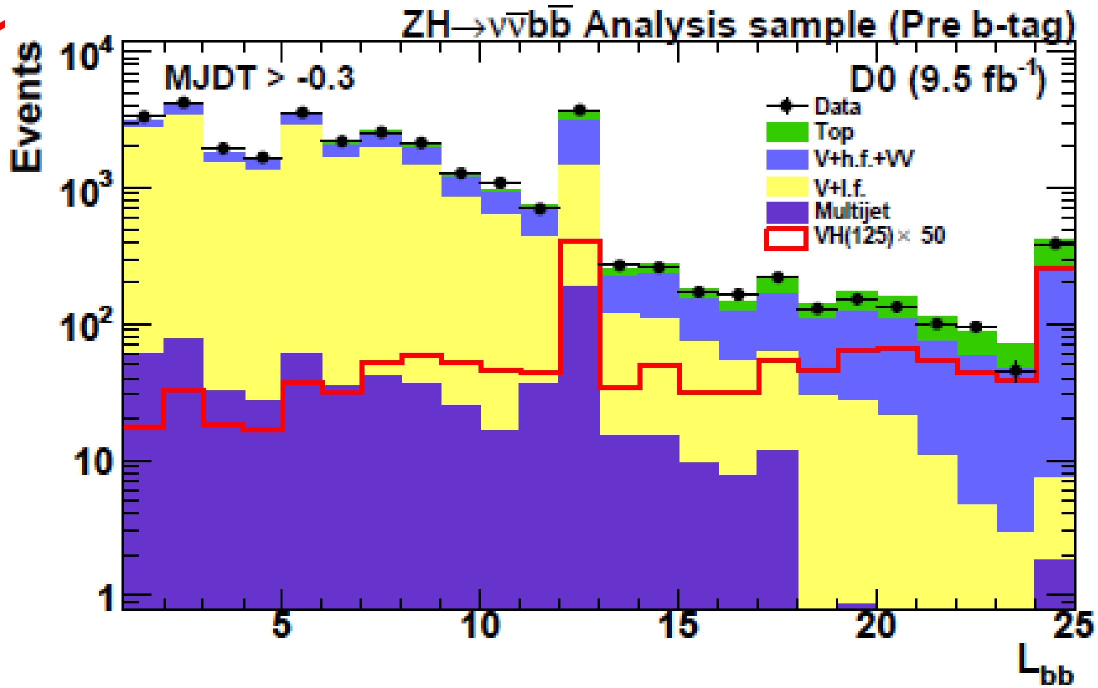
Reduce the background by tagging b-quark jets

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

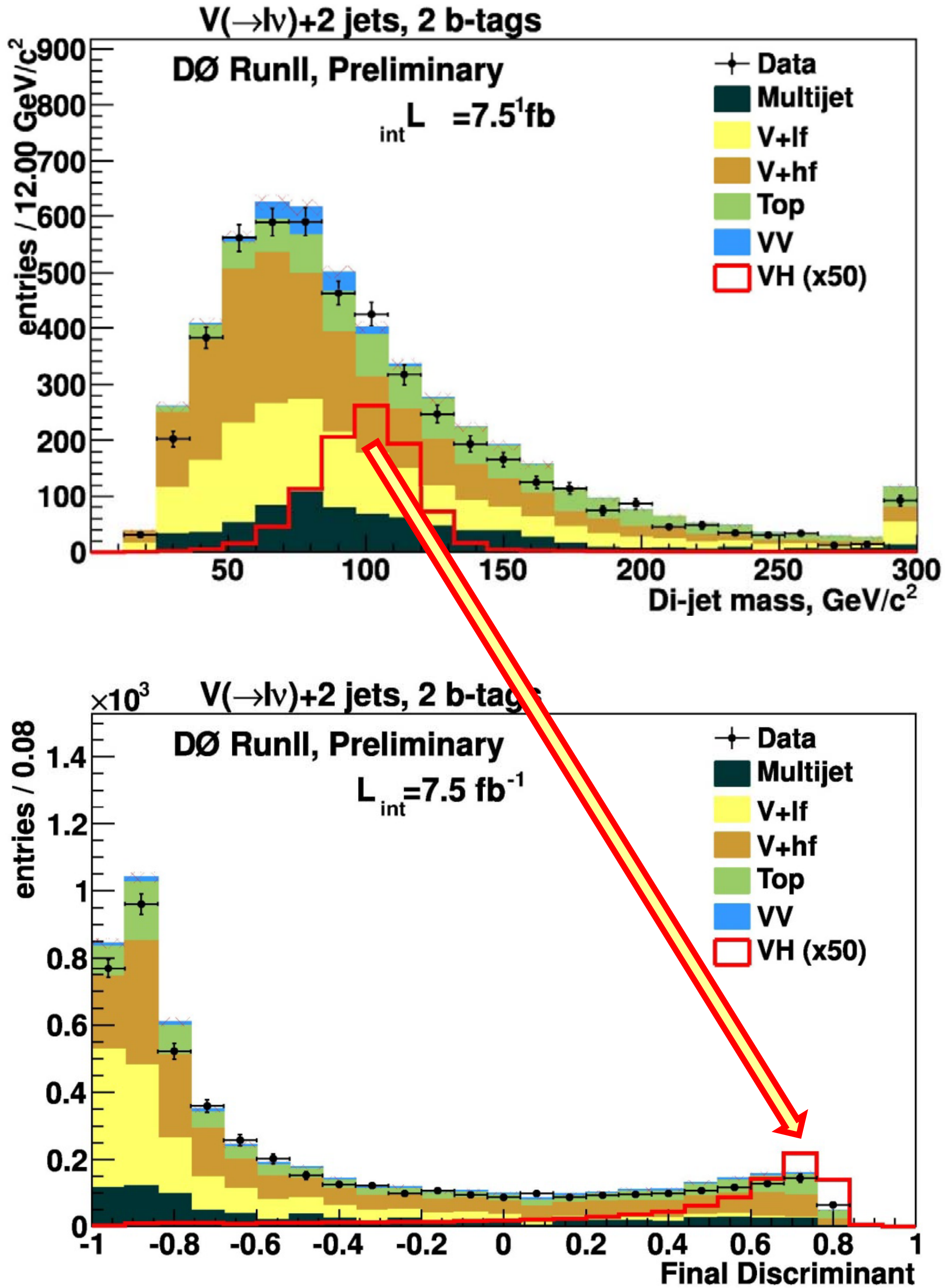


From Dijet mass to Multi Variate Analysis

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

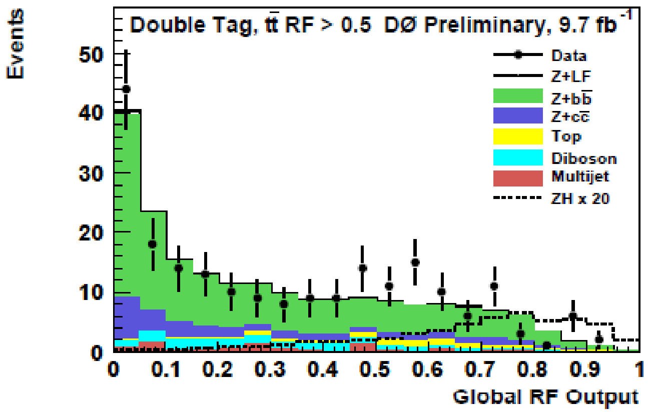
  Or use Matrix Element Calculations to determine probability for an event to be signal or background like

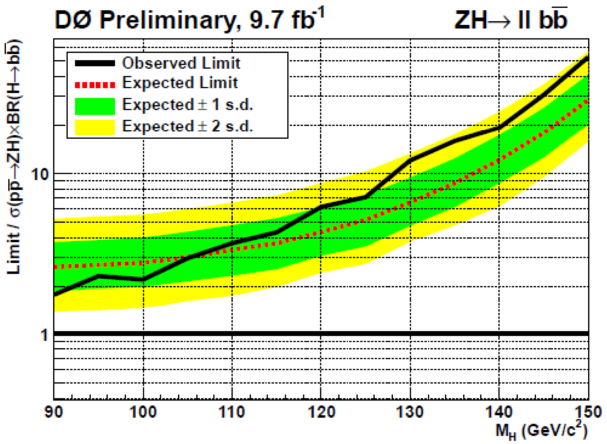
- **Approaches validated in Single Top observation @ Tevatron**
- **Combine these approaches**
- **Visible gain obtained (~25% in sensitivity)**



Latest/Final Results from DØ

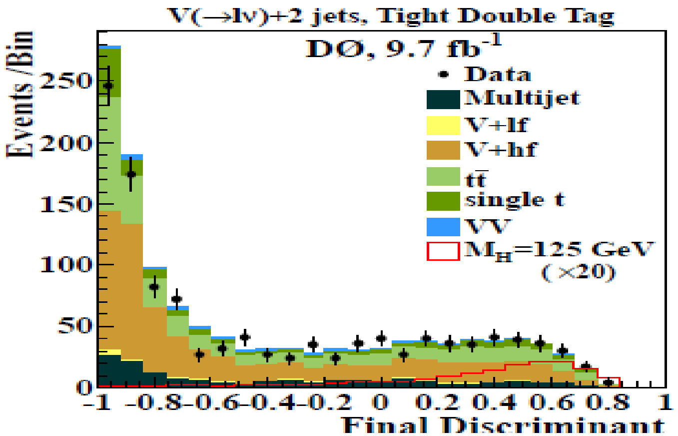
ZH→llbb ∫Ldt=9.7fb^{-1}

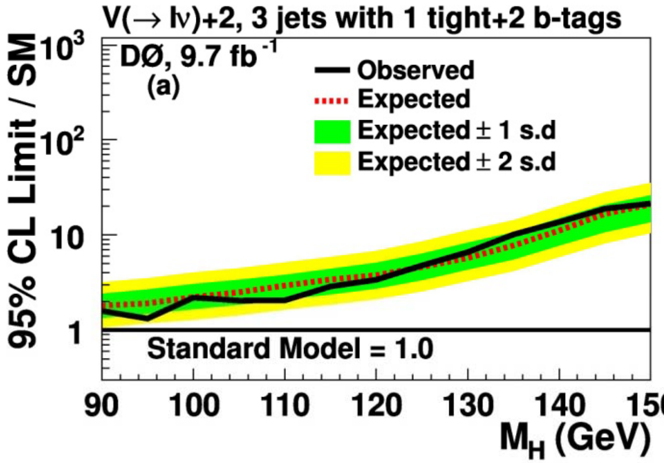




95% CL Exp (obs)
Limit **5.1** (**7.1**) x SM
@ MH=125 GeV

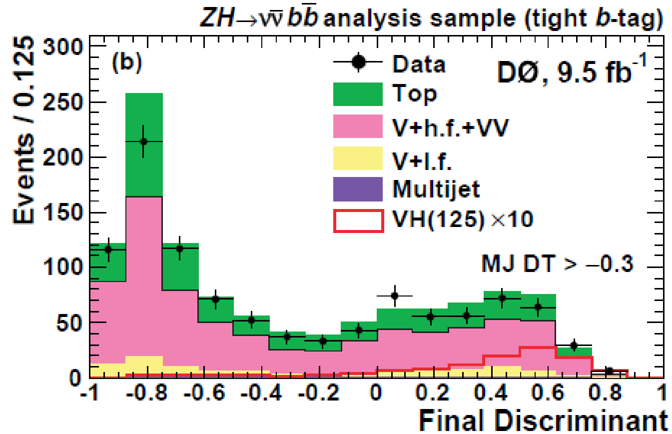
WH→lνbb ∫Ldt=9.7 fb^{-1}

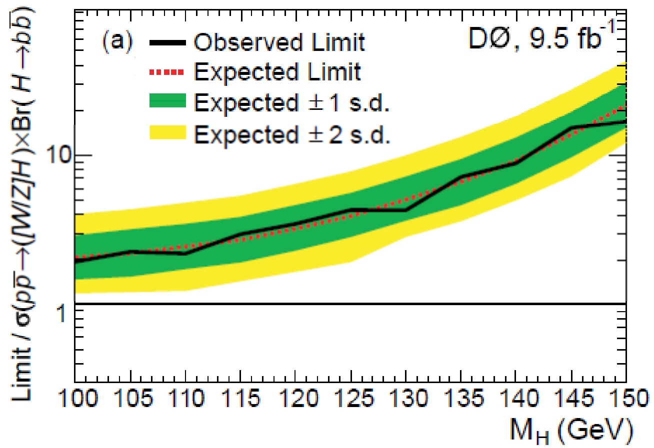




95% CL Exp (obs)
Limit **4.7** (**4.8**) x SM
@ MH=125 GeV (updated 01/13)

ZH→ννbb ∫Ldt=9.5 fb^{-1}



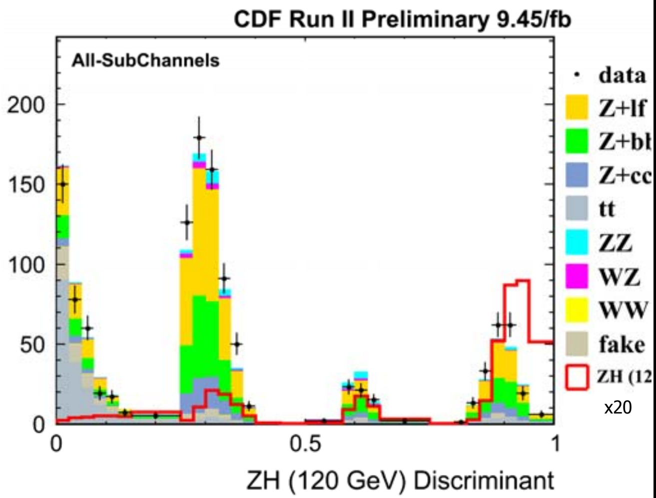


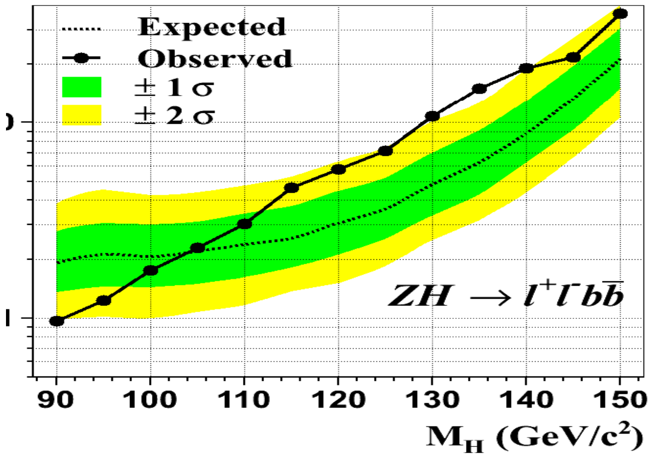
95% CL Exp (obs)
Limit **3.9** (**4.3**) x SM
@ MH=125 GeV

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

Latest/Final Results from CDF

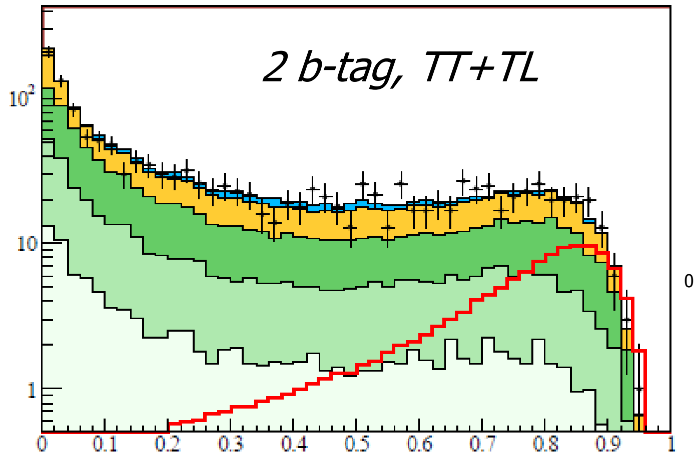
ZH→llbb̄ ∫Ldt=**9.5** fb^{-1}

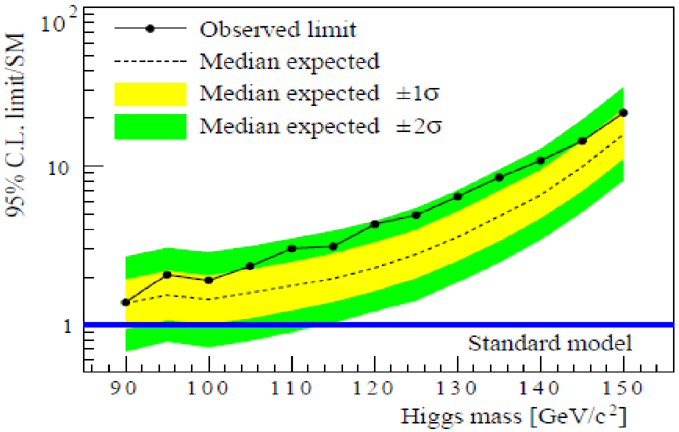




95% CL Exp (obs)
Limit **2.6** (**4.7**) x SM
@ MH=125 GeV

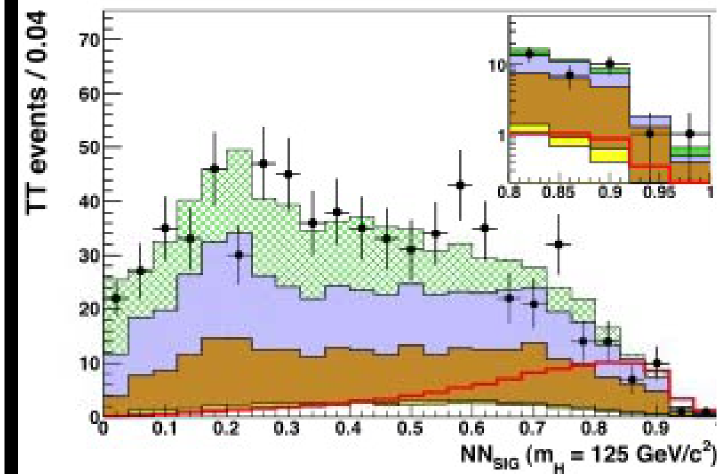
WH→lνbb̄ ∫Ldt=**9.5** fb^{-1}

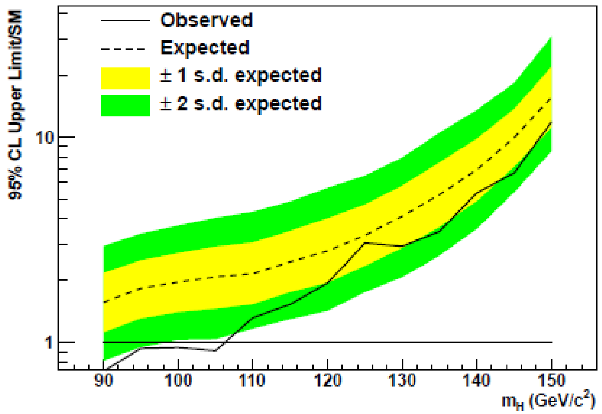




95% CL Exp (obs)
Limit **2.8** (**4.9**) x SM
@ MH=125 GeV

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

<u>For m_H=125 GeV</u>

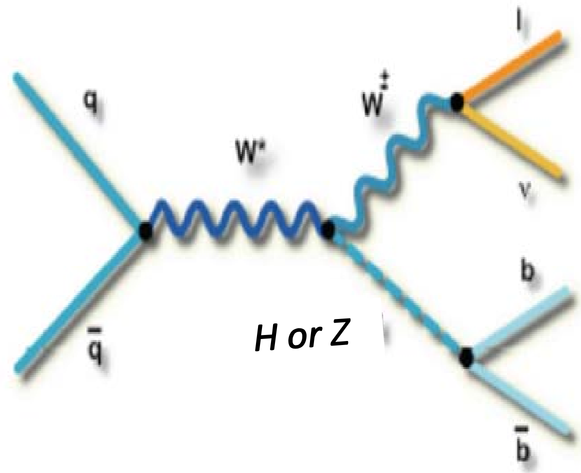
WH→lνbb: σ = 16 fb
ZH→ ννbb:σ = 9 fb
ZH→ llbb: σ = 3 fb

Total VH: σ = 28 fb

<u>Replace H with Z</u>

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

Total VZ: σ = 202 fb

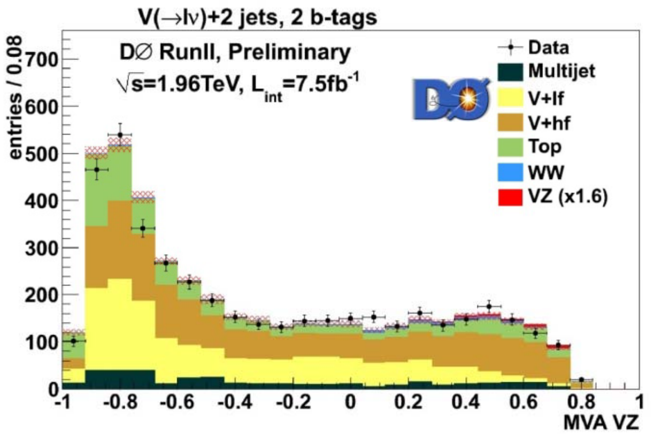


VZ yield is ~7 times larger than VH (125 GeV),,but VZ→Vbb has much more W+jets backgrounds, and difficult background from WW, so VZ sensitivity only ~3 times higher than VH

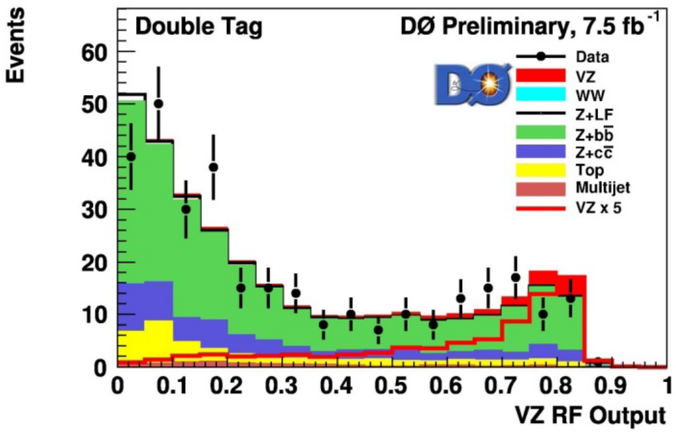
Apply similar analysis as low mass H→bb analysis, and check sensitivity.

Benchmarks : Dibosons to Heavy Flavor

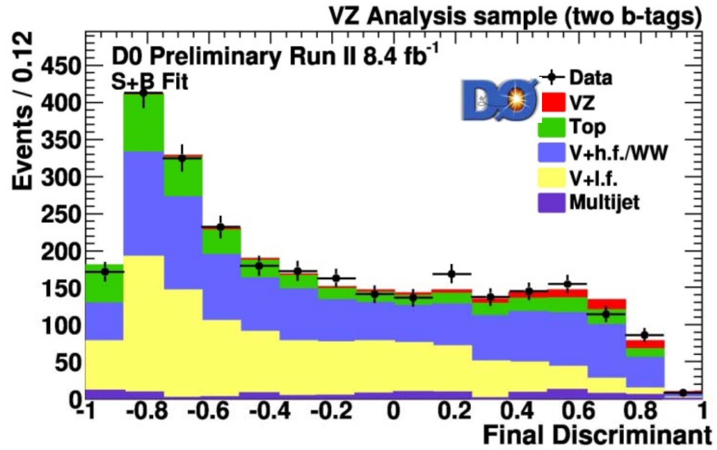
Diboson lvbb



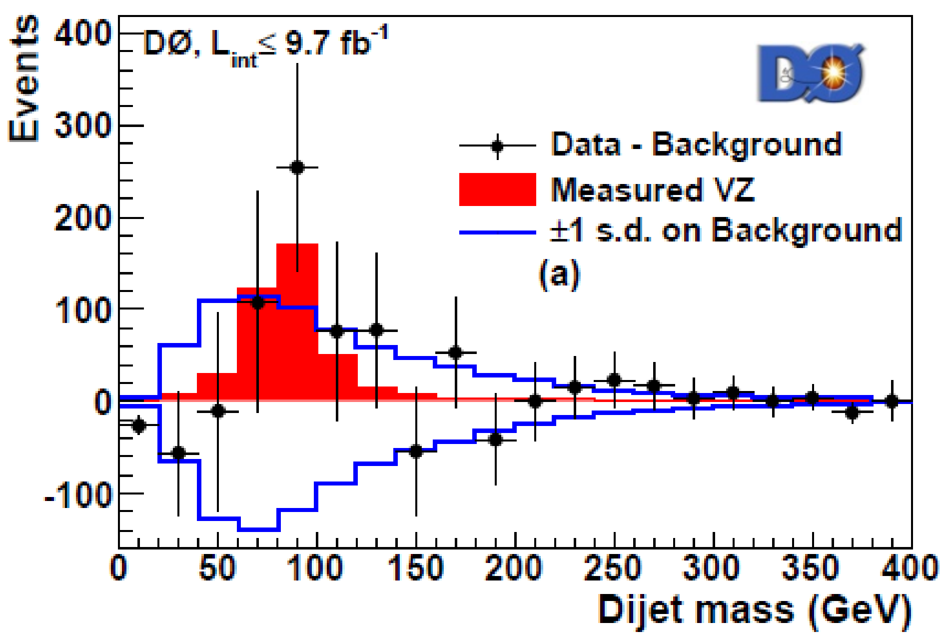
Diboson llbb

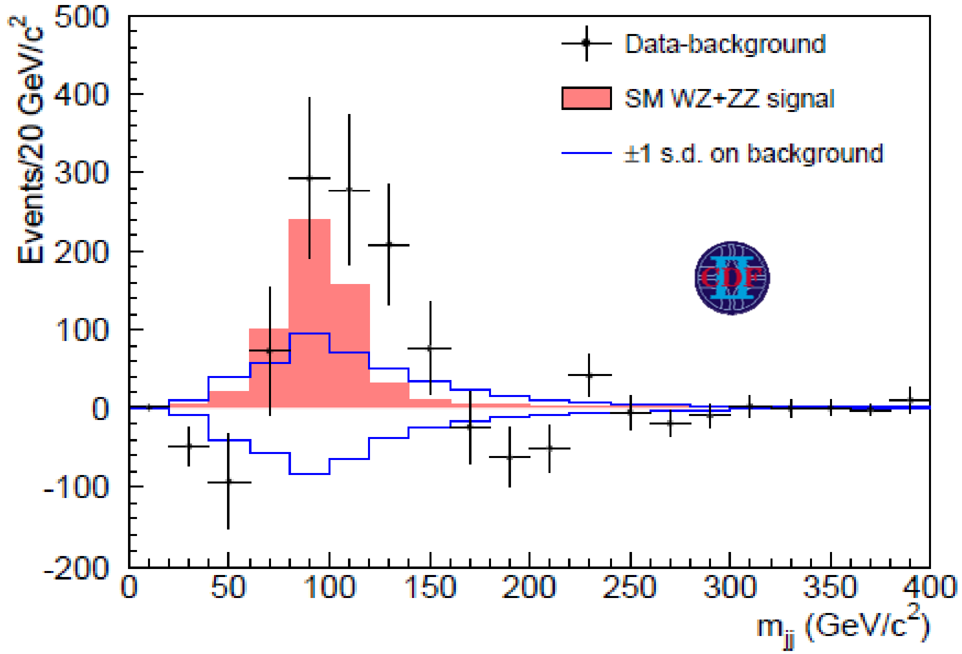


Diboson vvbb



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



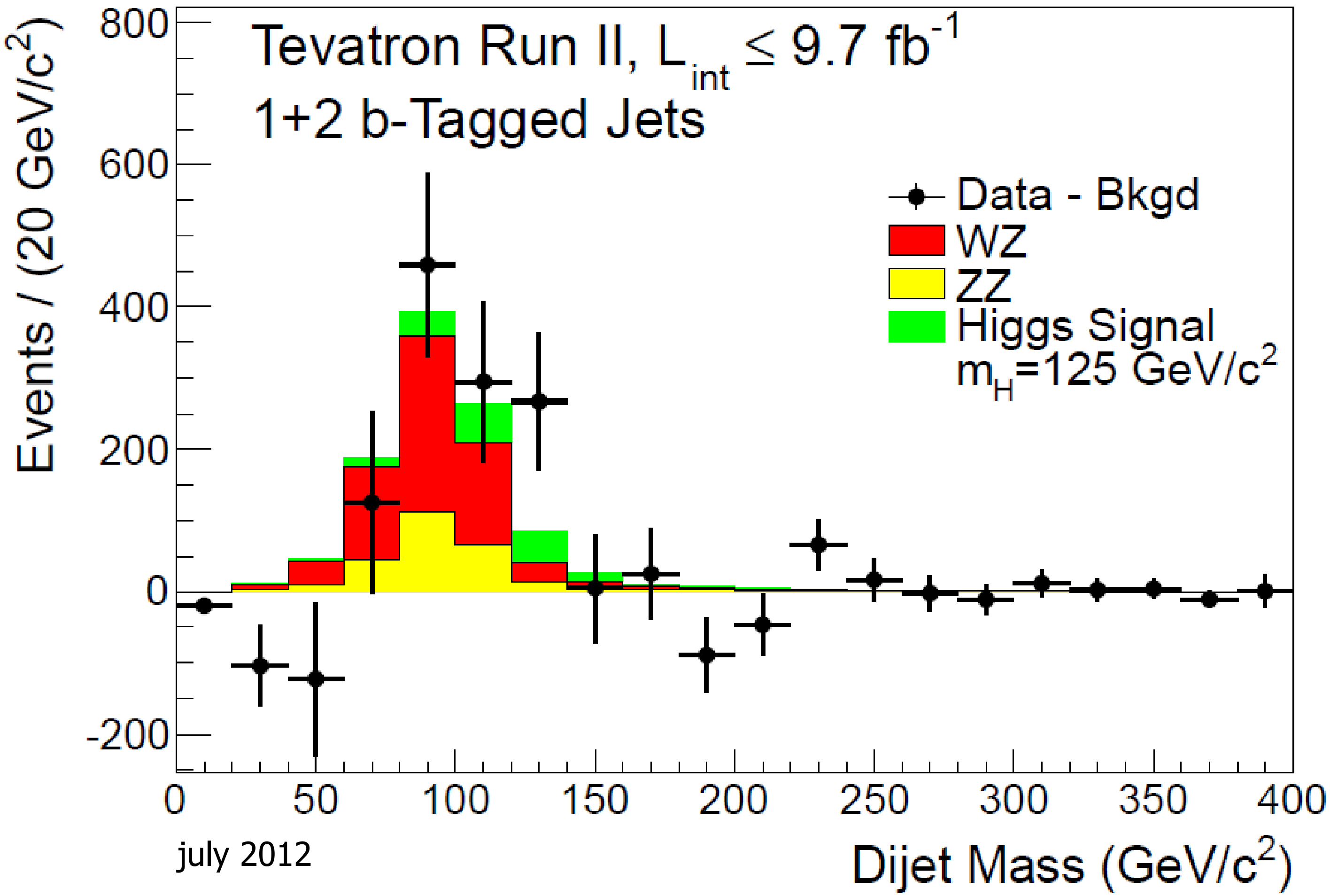


Benchmarks : Dibosons to Heavy Flavor

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)



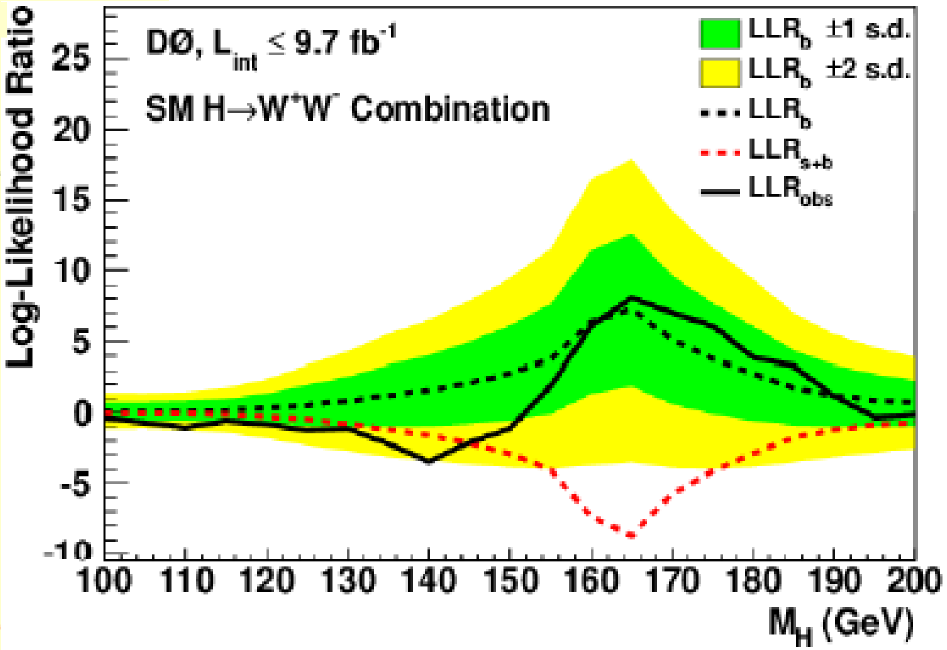
july 2012

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

Higgs Sensitivity / Log Likelihood Ratio plot

Background-like outcomes

Signal-like outcomes



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

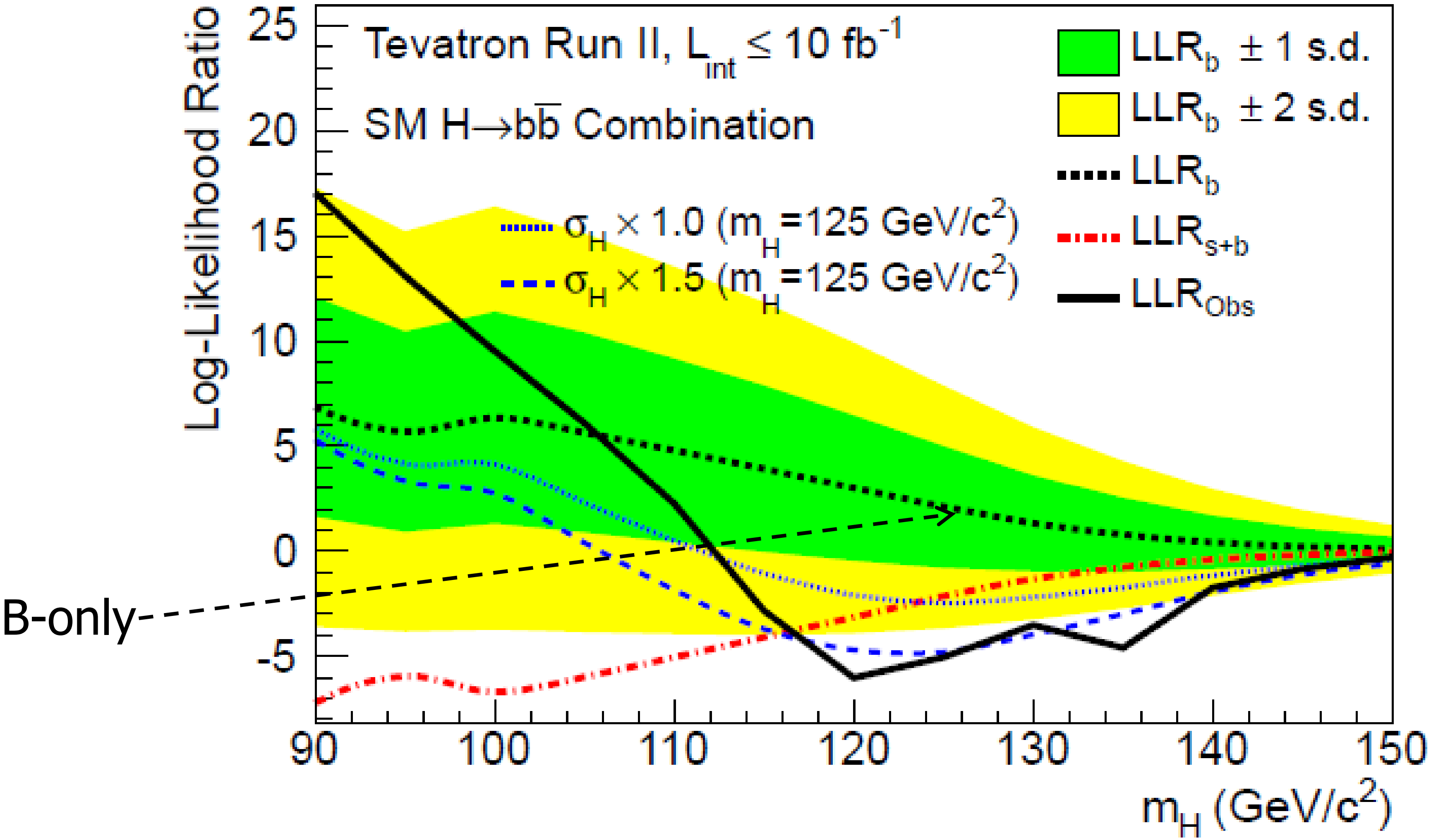
P - Poisson likelihood of B or S+B hypothesis

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

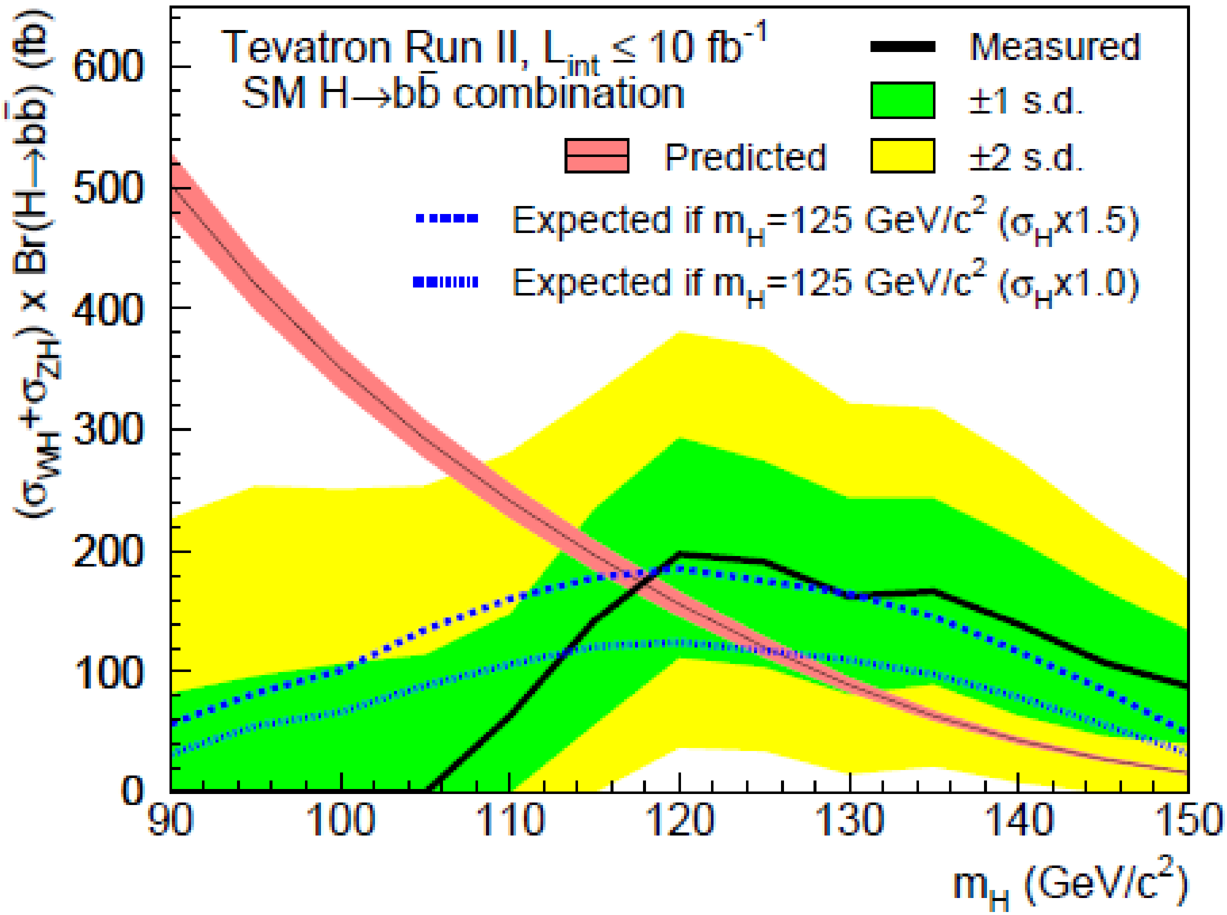
The value of LLR_{obs} relative to LLR_{s+b} and LLR_b indicates whether the data distribution appears to be more like signal-plus-background or background-only.

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

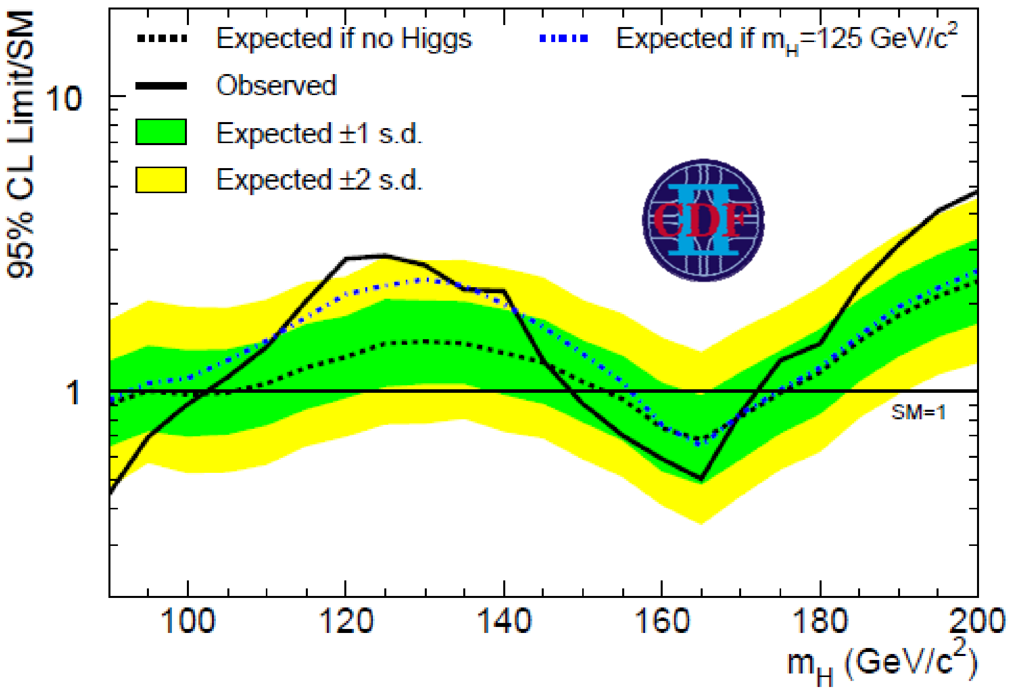


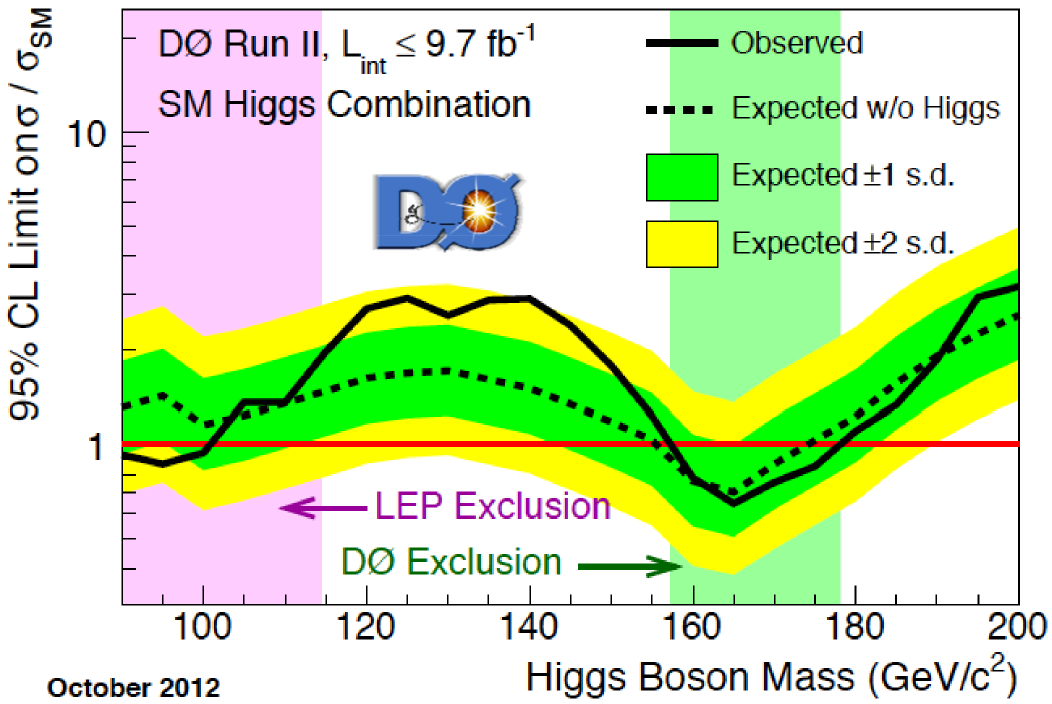
$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow b\bar{b}) = 0.19 \pm 0.09 \ (\text{stat} + \text{syst}) \ \text{pb}$$

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)





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

Observed 95% CL exclusion:

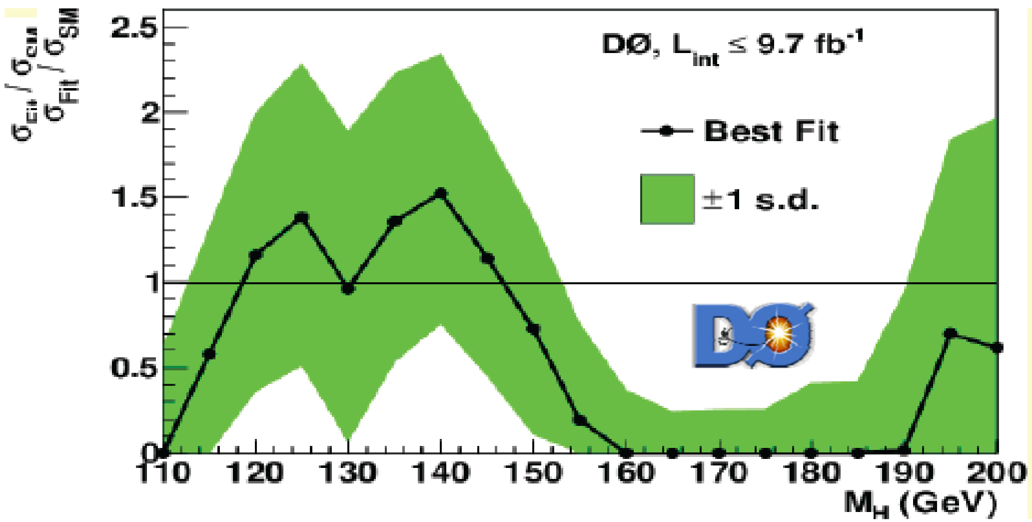
$90 < m_H < 101$ GeV, $157 < m_H < 178$ GeV

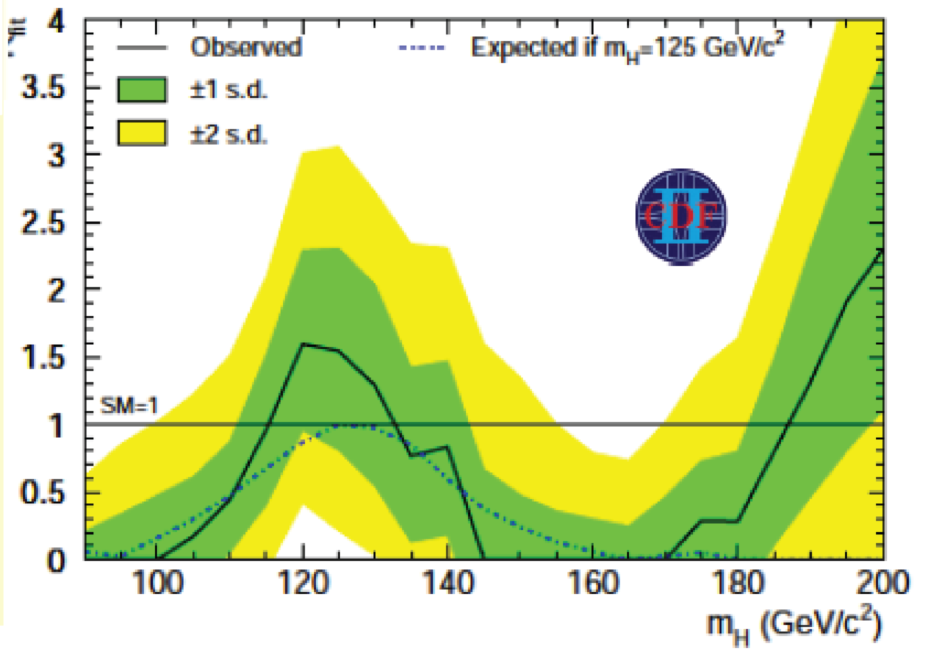
At m_H = 125 GeV:
Exp. limit: 1.46 x SM
Obs. limit: 2.89 x SM

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



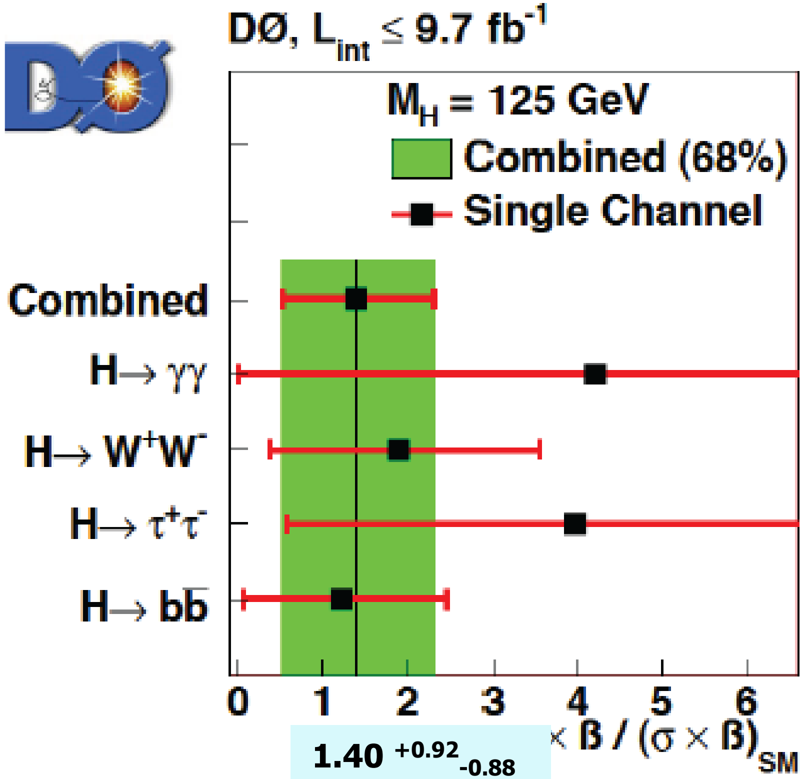


$1.40^{+0.92}_{-0.88}$

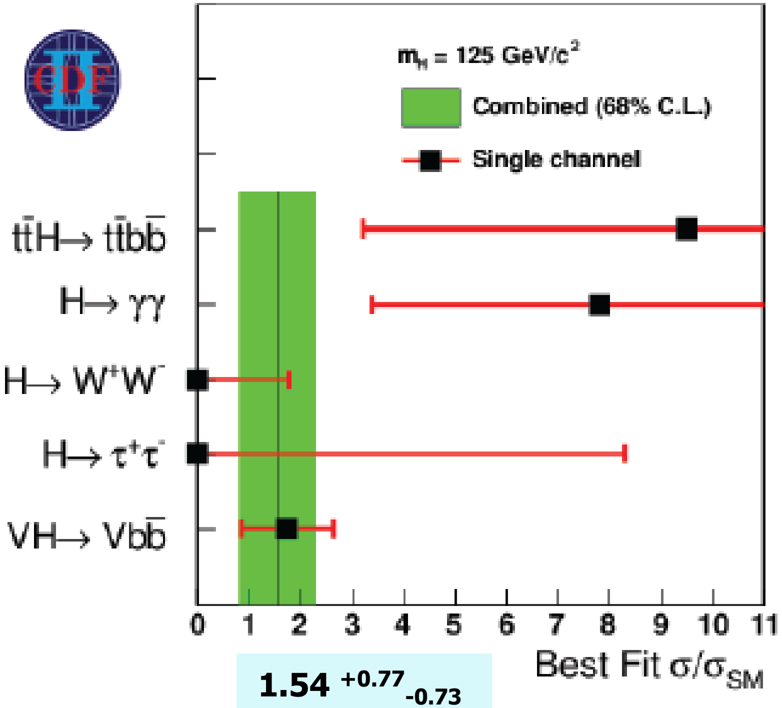
$1.54^{+0.77}_{-0.73}$

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	$9.49^{+6.60}_{-6.28}$

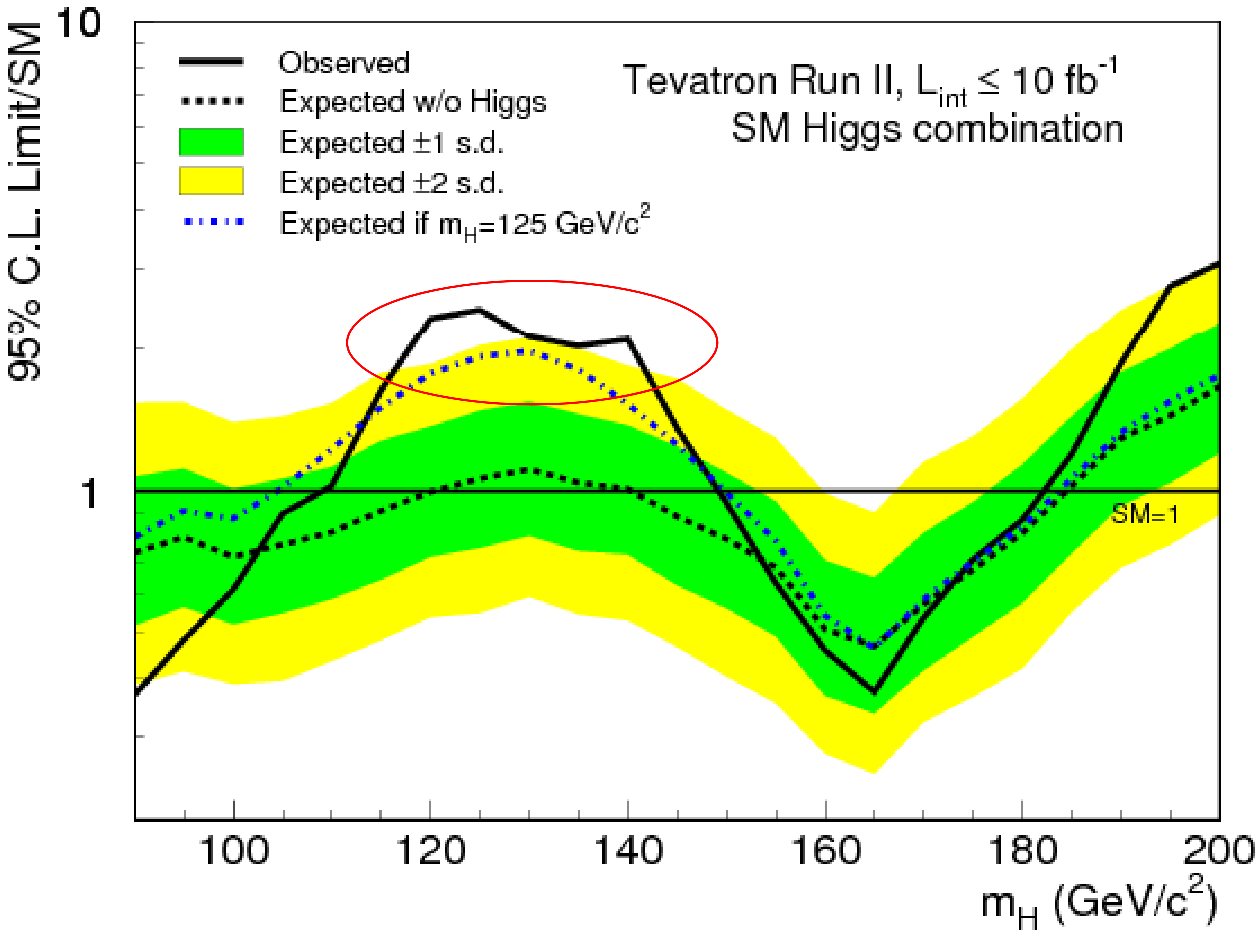


$1.40^{+0.92}_{-0.88}$

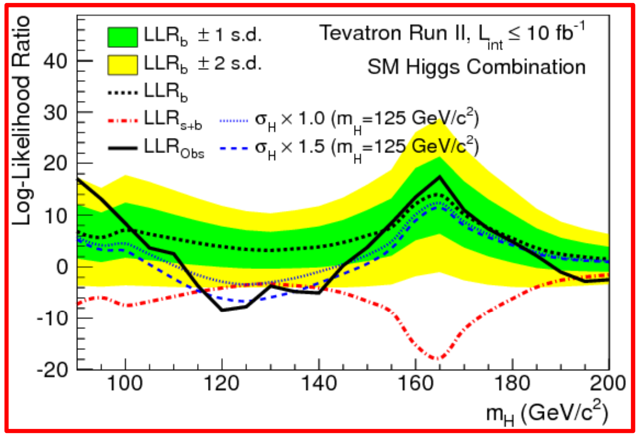


$1.54^{+0.77}_{-0.73}$

Full Tevatron combination



LLR plot

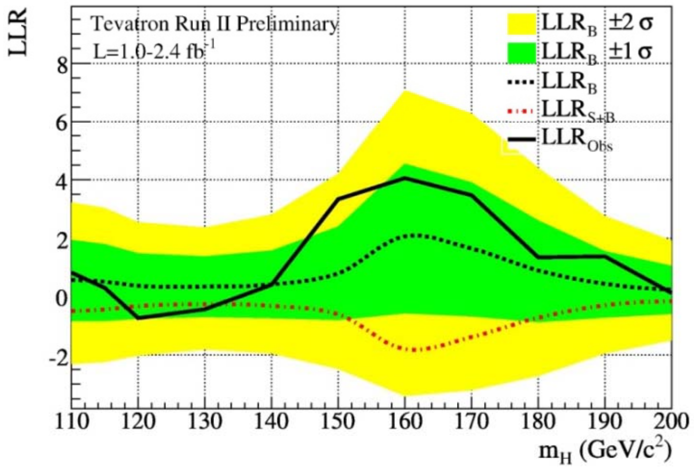


Significant excess, 2-3 sigma for 115→140 GeV

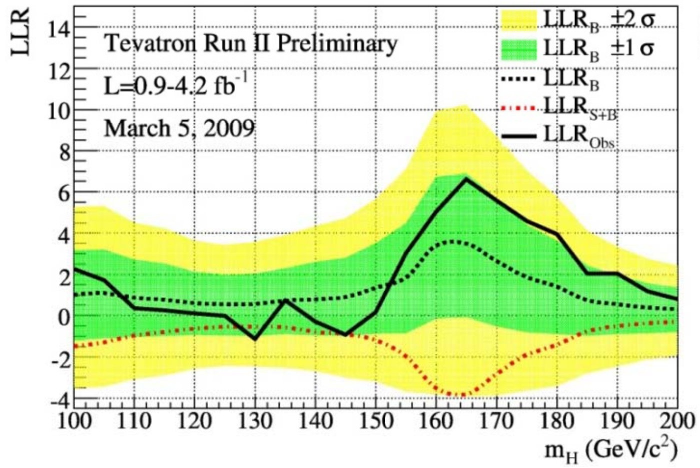
- Expected exclusion: 90 < m_H < 121 GeV, 140< m_H < 184 GeV
  Observed exclusion: 90 < m_H < 107 GeV, 149 < m_H < 182 GeV
- 95% CL limit at m_H=125 GeV: 1.09xSM (expected), 2.49xSM (observed)

History of Tevatron results: LLR of all searches

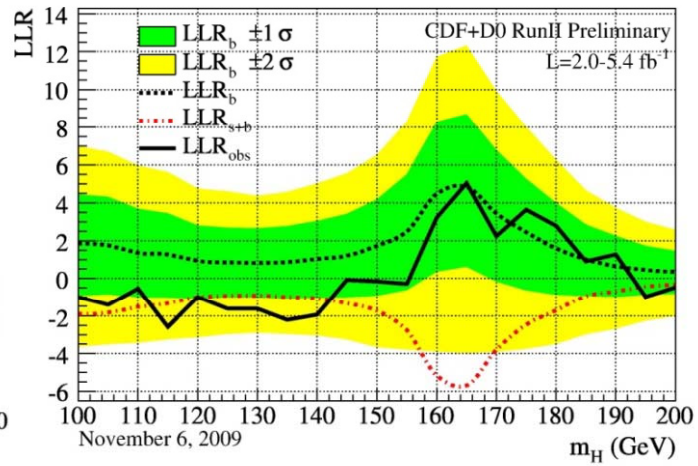
Data of 2007; up to 2.4 fb^{-1}



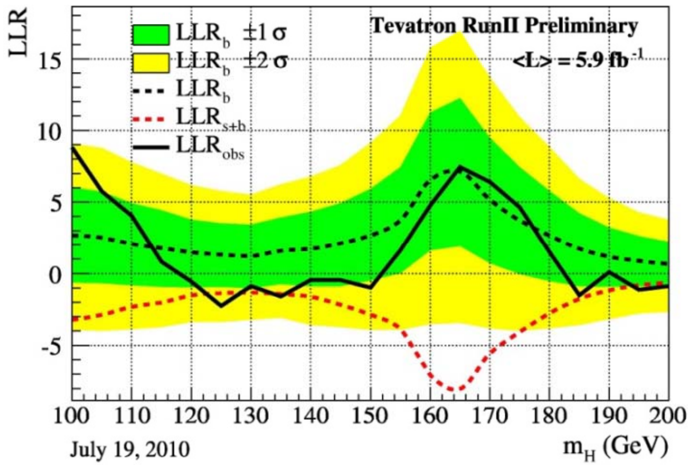
Data of 2008; up to 4.2 fb^{-1}



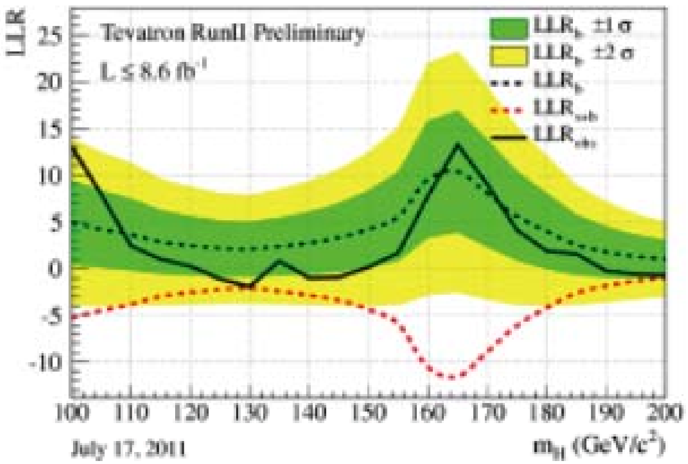
Data of mid 2009; up to 5.4 fb^{-1}



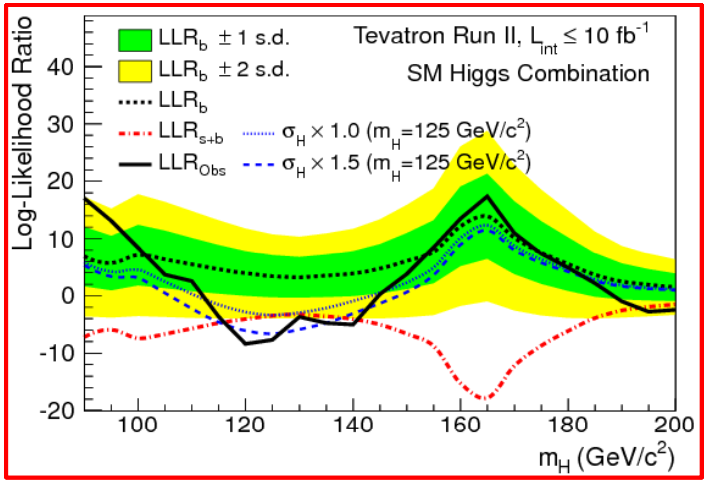
Time



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



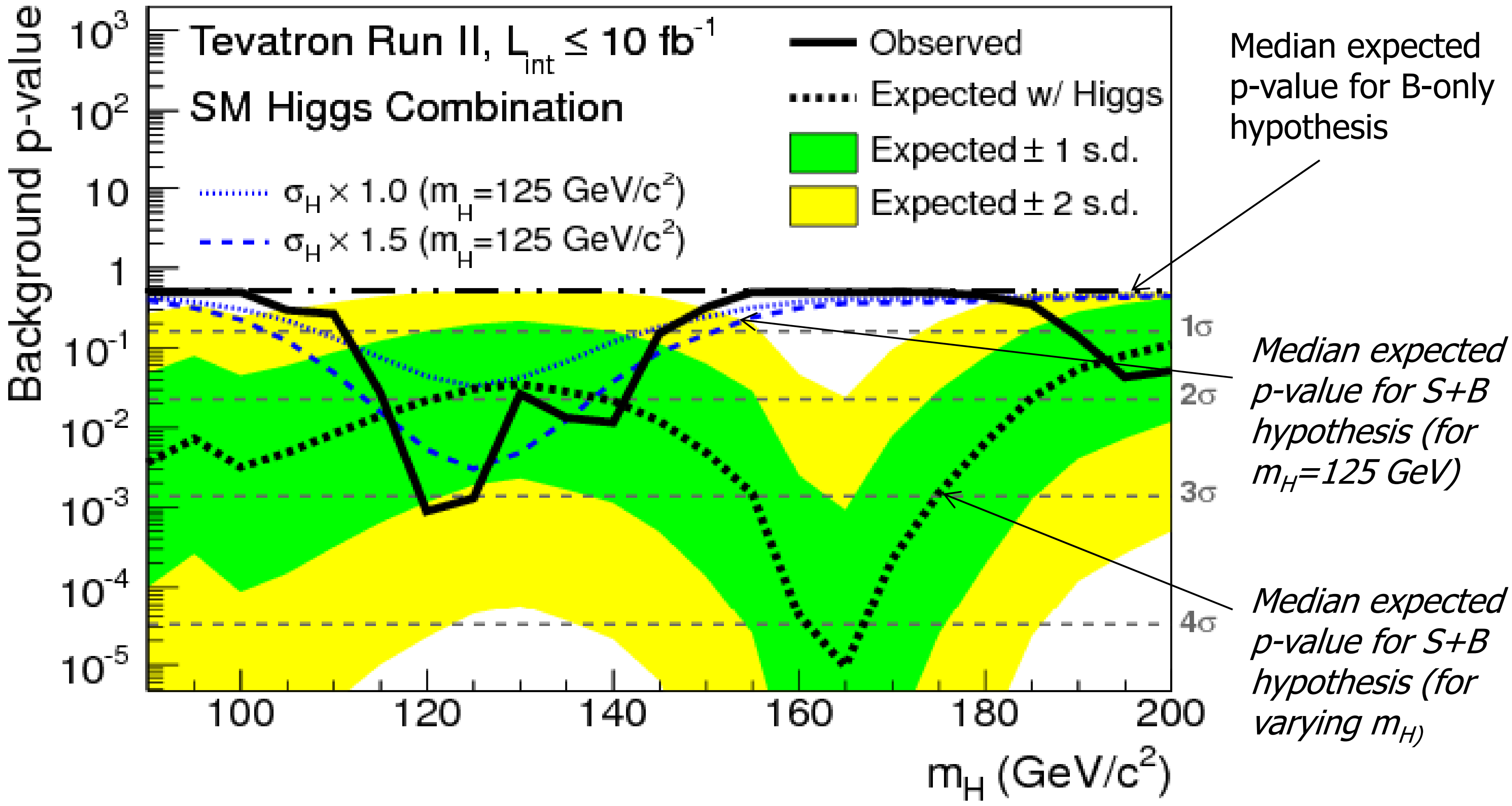
Data of mid 2011; up to 8.6 fb^{-1}



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

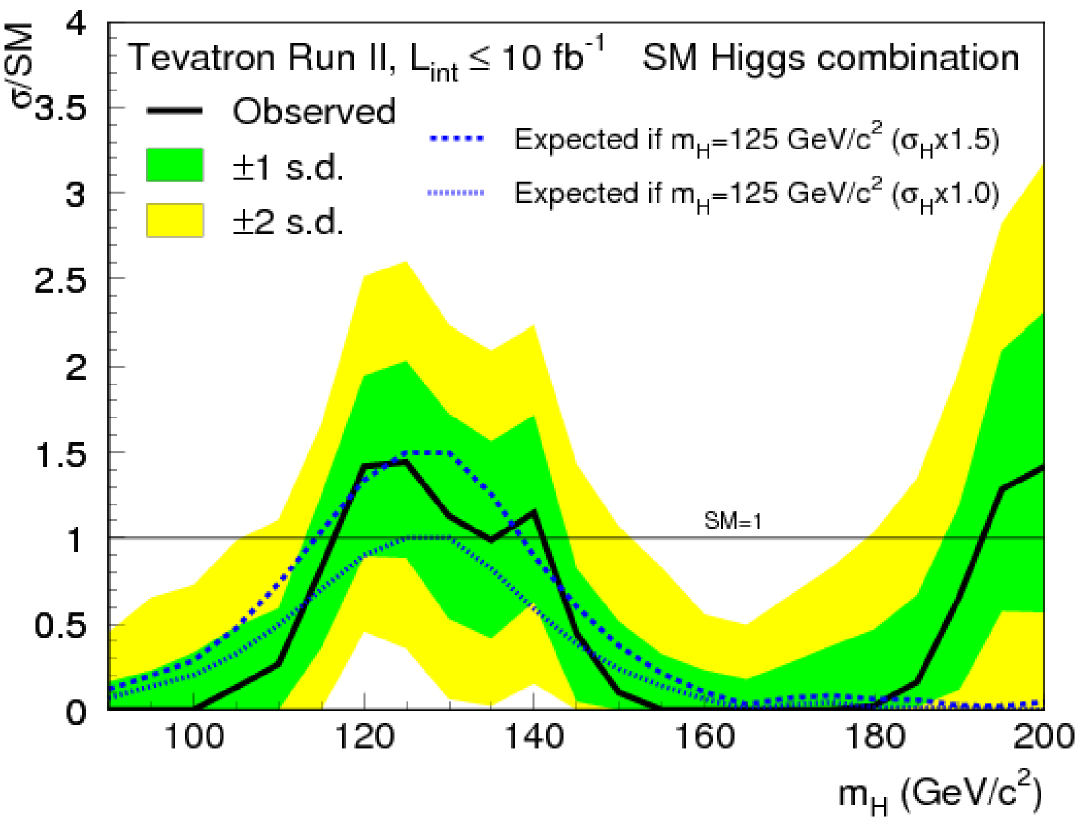
Quantifying the Excess: p-values

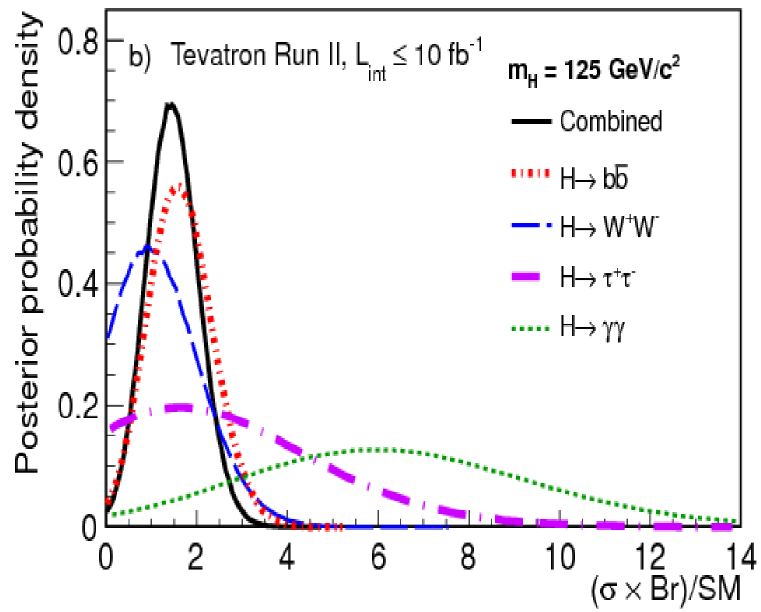
- Local p-value distribution for background-only hypothesis:



local p-value at m_H=125 GeV: 3.0σ (2σ expected)

Quantifying the signal: Best Fit Signal Rate



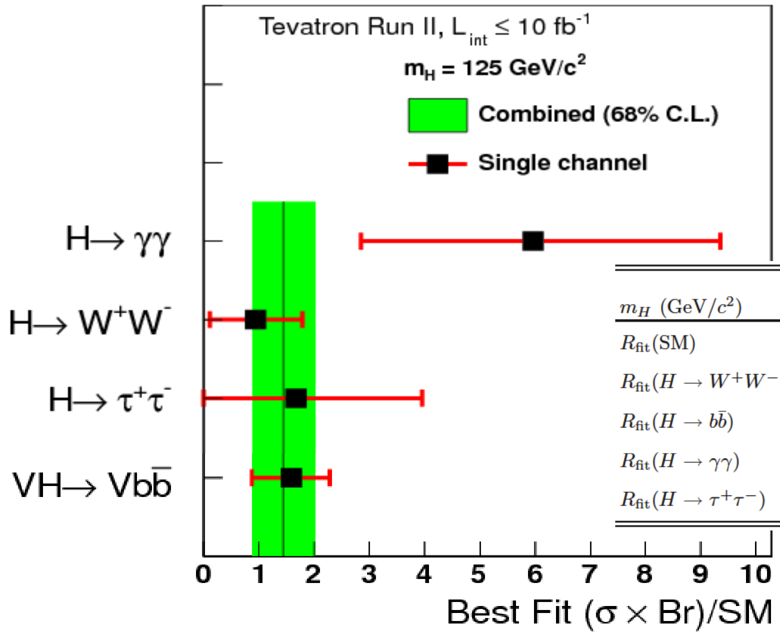


- Maximum likelihood fit to data with signal rate as free parameter.
- Best-fit signal rate at m_H=125 GeV:

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

Consistent with SM Higgs.

Reasonably consistent across channels.



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

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:

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

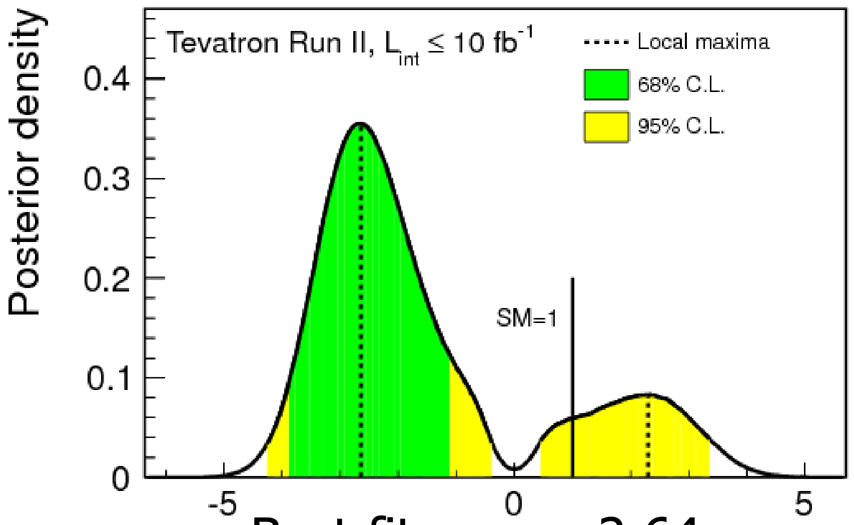
$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

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

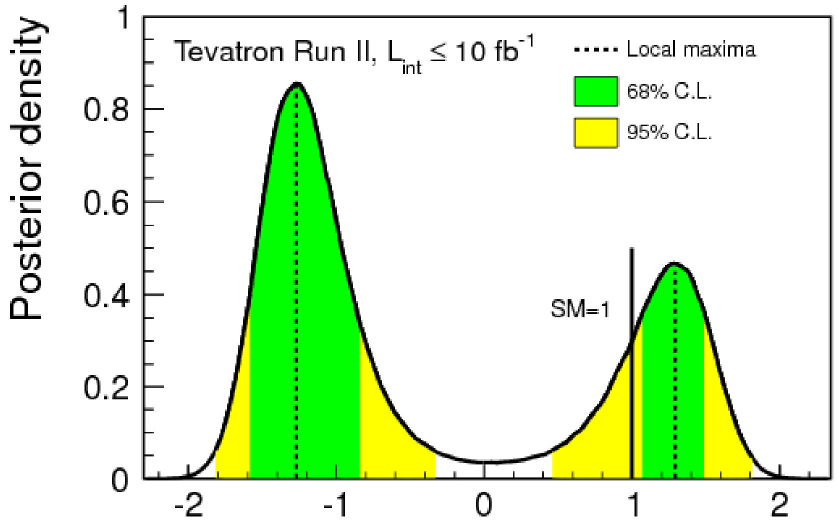
$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, M_H)$$

Probing Higgs Boson Coupling (I)

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



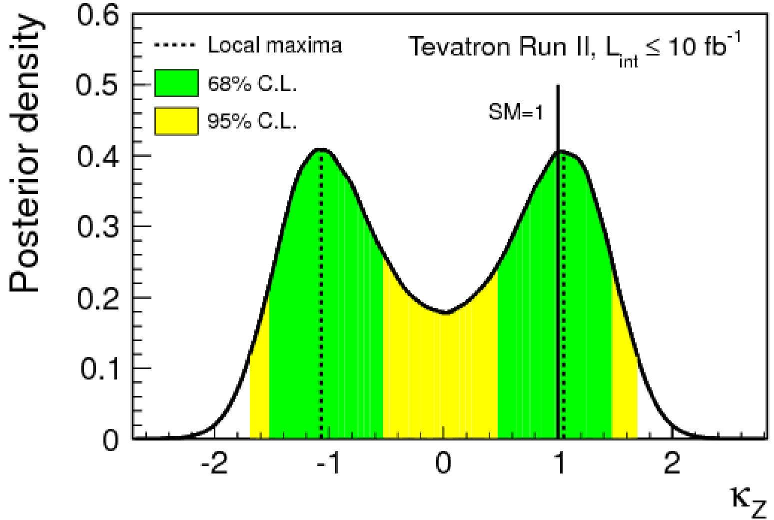
Best fit: $\kappa_f = -2.64$



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 $H \rightarrow \gamma\gamma$

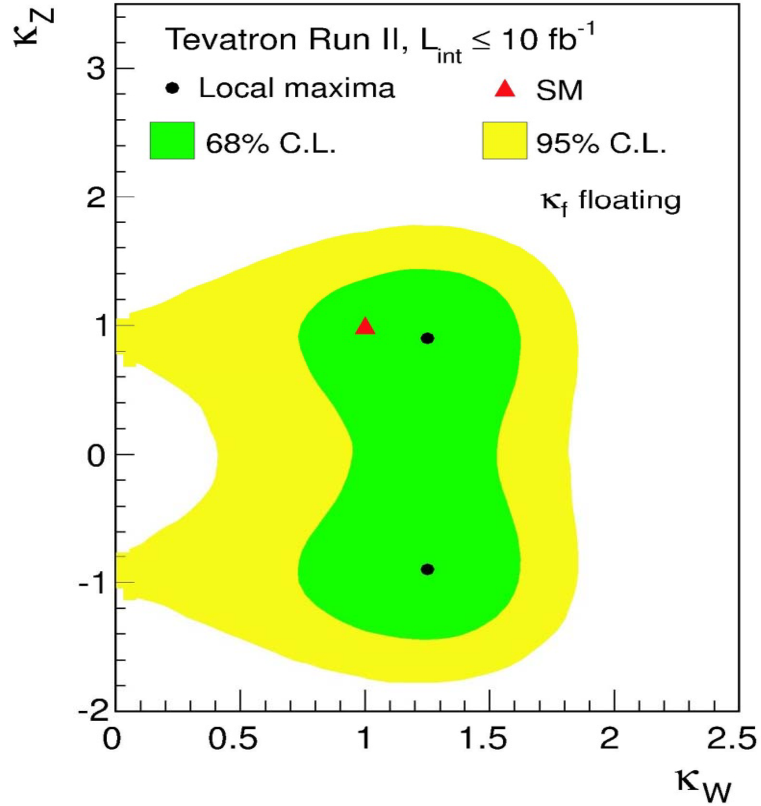
- Sensitivity to κ_Z mainly though $ZH \rightarrow llbb$, $\nu\nu$ nearly symmetric
  - Best fit: $\kappa_Z = \pm 1.05$



Probing Higgs Boson Couplings (II)

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

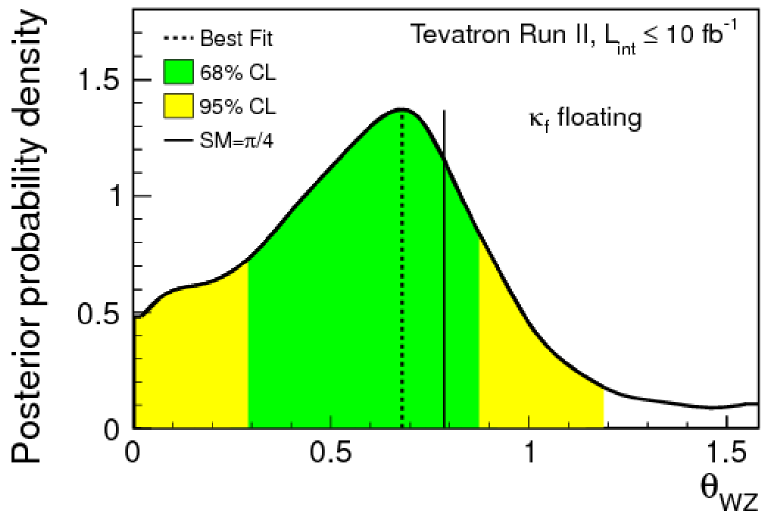
- The point $(\kappa_W, \kappa_Z) = (0, 0)$ corresponds to NO Higgs boson production or decay in the most sensitive search modes at the Tevatron and is not included within the 95% C.L. region due to the significant excess of events in the SM Higgs boson searches @ 125 GeV



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

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

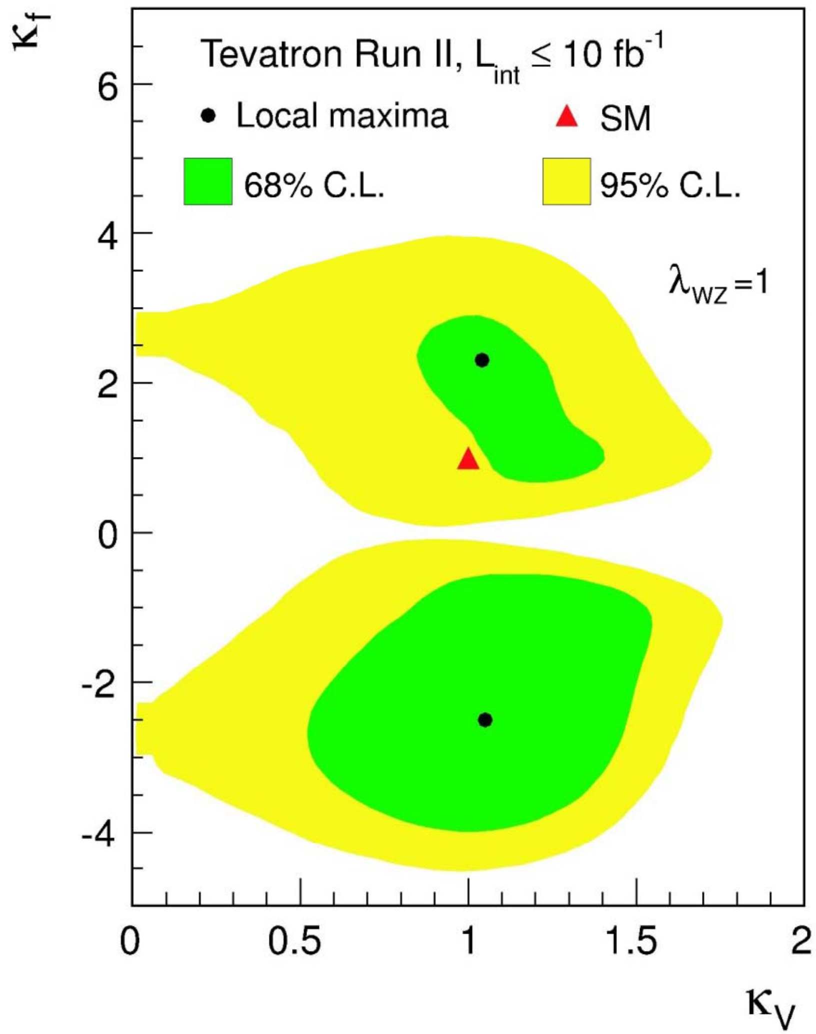
$$\theta_{WZ} = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$



Probing Higgs Boson Couplings (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:
  (κ_V, κ_f)=(1.05,−2.40) and
  (κ_V, κ_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.

- Published evidence for WX/ZX production with X→bb (7/2012), 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 integrated Luminosity and center of mass energy.

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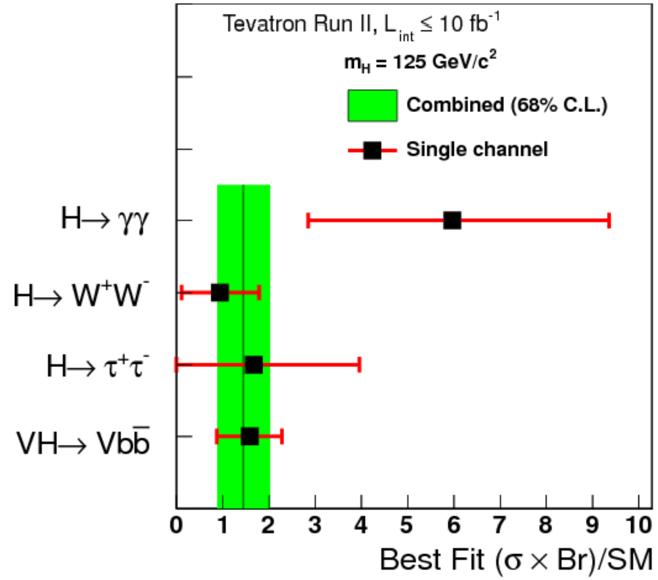
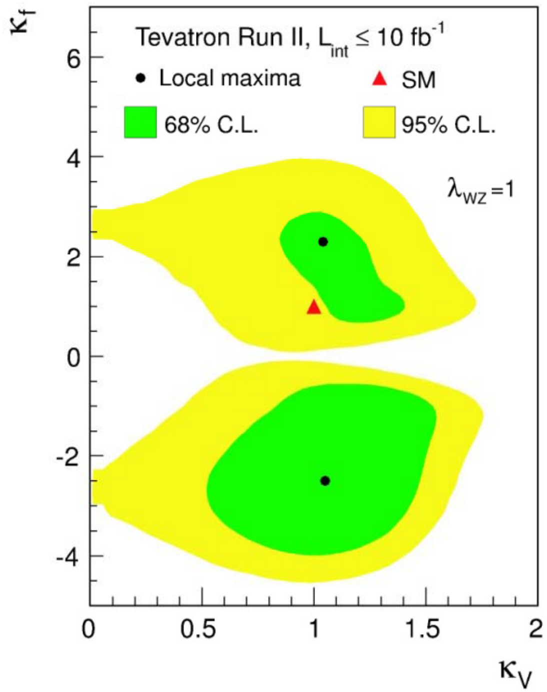
- Signal strengths in 4 decay channels, and results on Higgs couplings to fermions, W, and Z, are consistent with the SM.

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

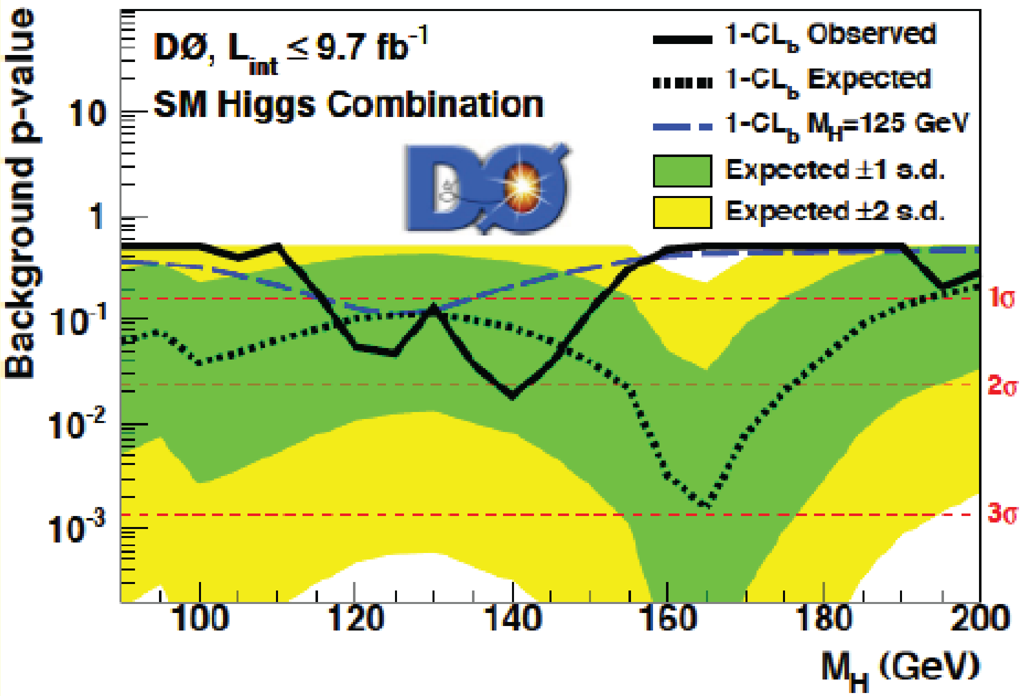


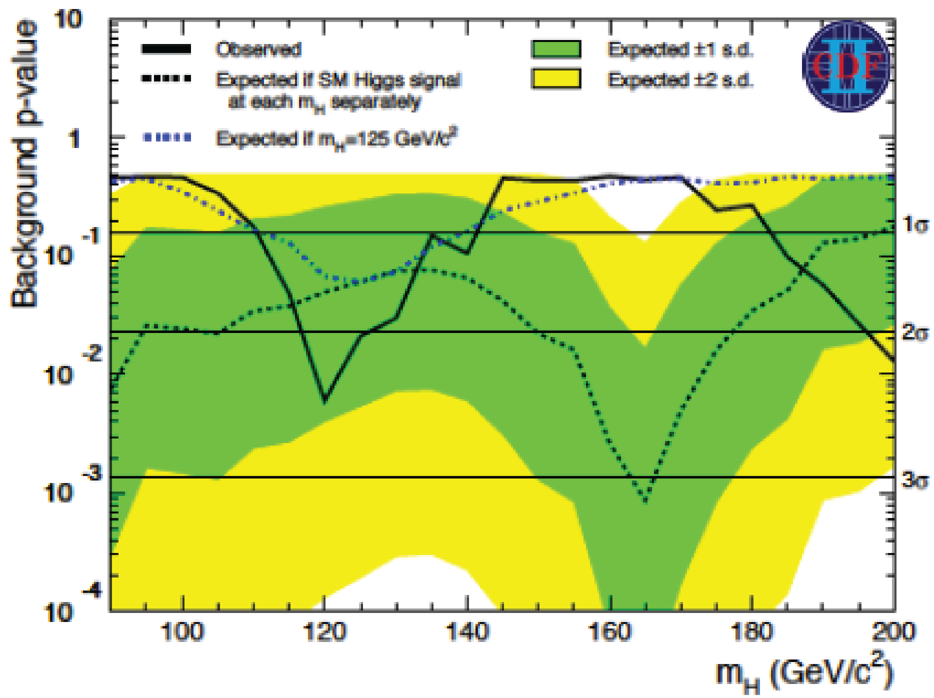


Backup Slides

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

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

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

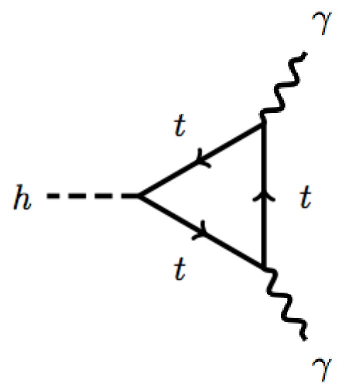
$$\Gamma(H \to ff) = \Gamma(H \to ff)_{SM}\kappa_f^2$$

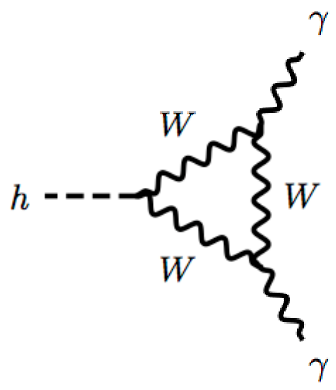
$$\Gamma(H \to gg) = \Gamma(H \to gg)_{SM}(0.95\kappa_f^2 + 0.05\kappa_f\kappa_V)$$

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

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

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:**

  $\kappa_W = -1.27^{+0.46}_{-0.29}$; *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)