

Review of Tevatron Higgs Results

SM@LHC 2013, Freiburg

9th April 2013

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For the DØ and CDF Collaborations

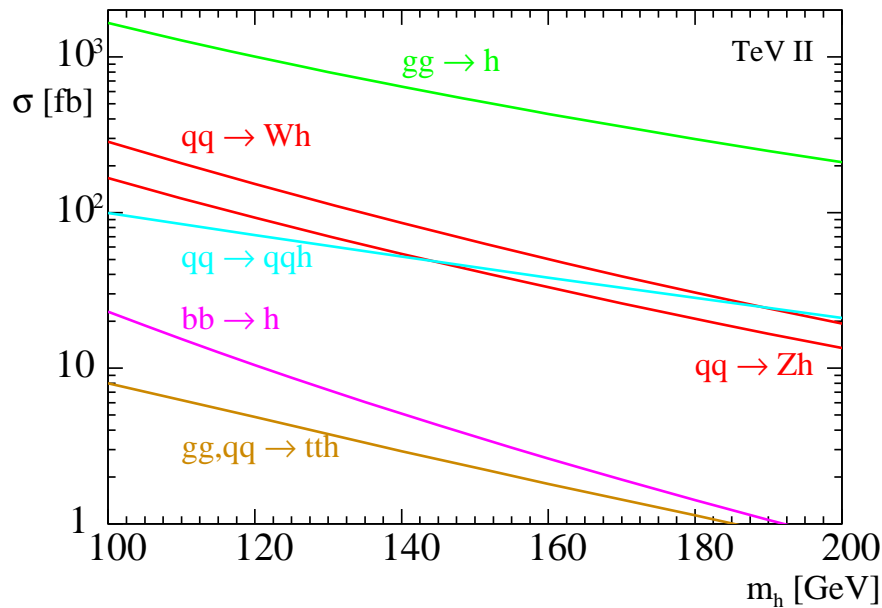
Outline

- Higgs @ Tevatron
- DØ & CDF
- $H \rightarrow b\bar{b}$ searches
- $H \rightarrow WW$ searches
- Tevatron Higgs combination
- Conclusion

Higgs @ Tevatron

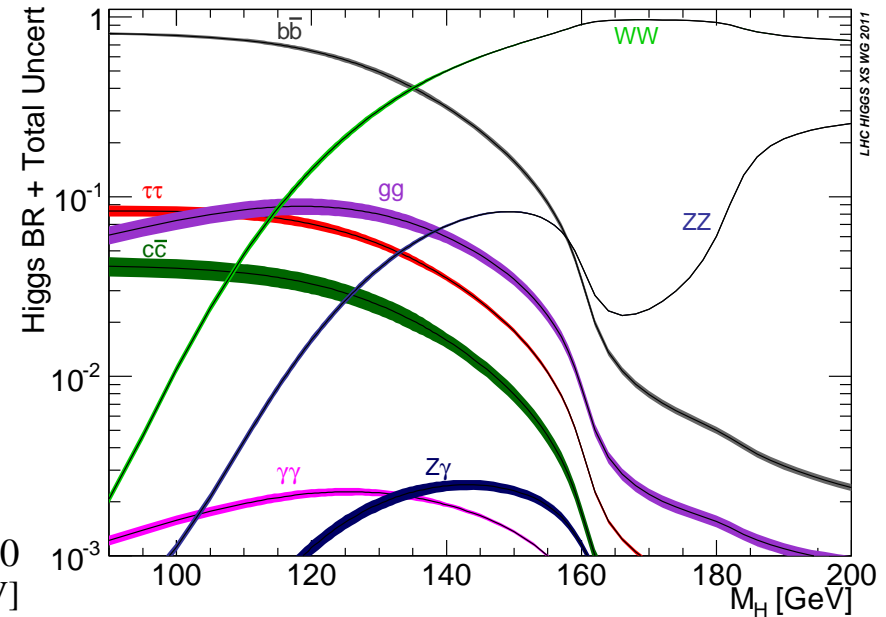
$p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

Higgs production



- Gluon fusion
- Associated production

Higgs decay

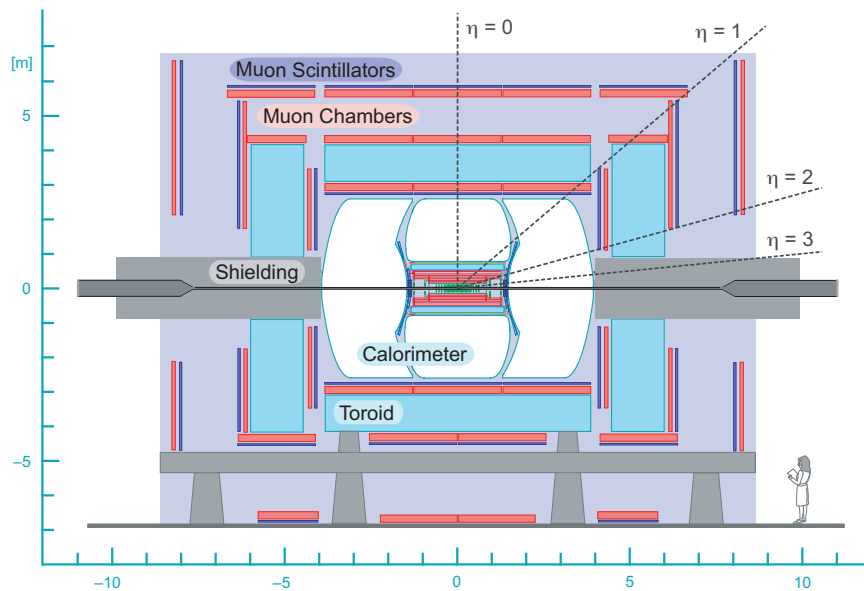


- $b\bar{b}$ at low m_H
- WW at high m_H

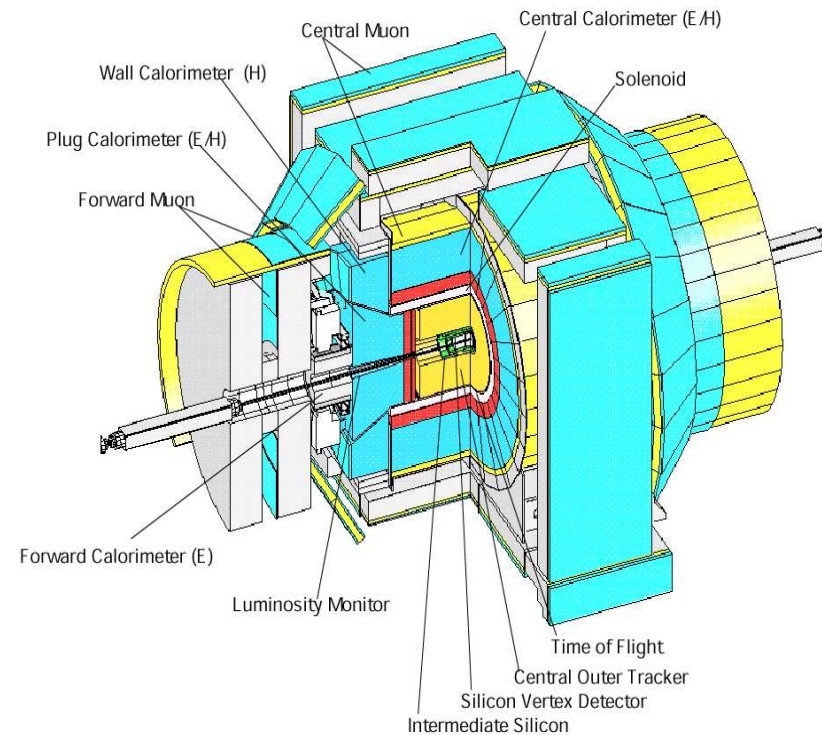
DØ & CDF

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- $\int \mathcal{L} dt > 10 \text{ fb}^{-1}$ recorded / experiment

DØ



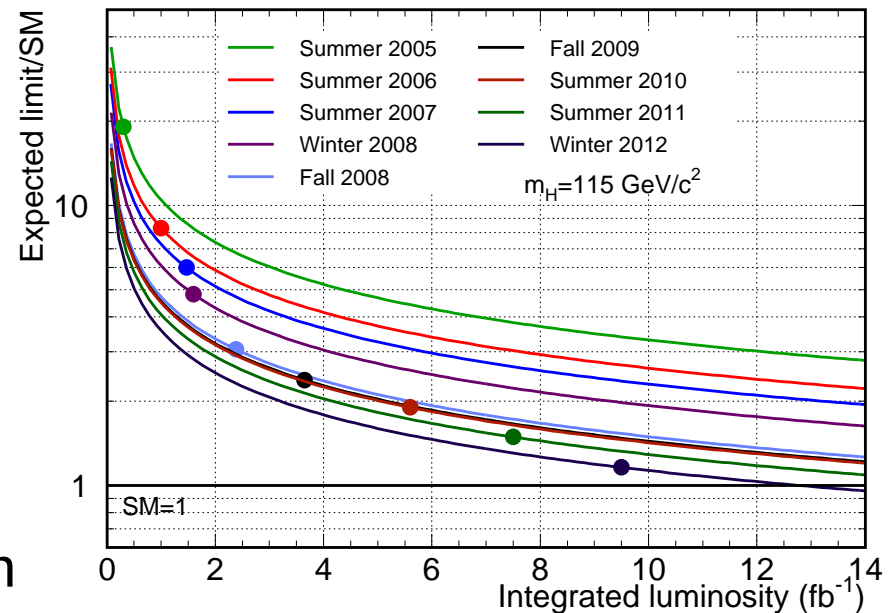
CDF



Higgs @ Tevatron Search History

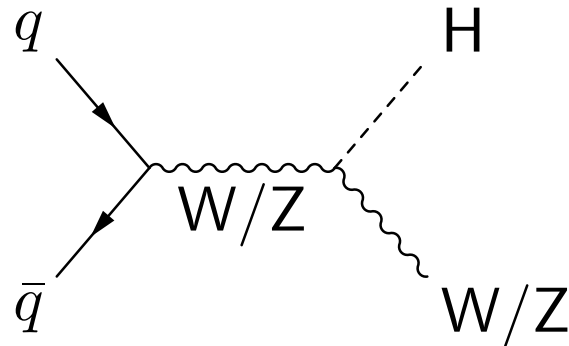
- Ten years of data & analysis
- Analyses improvements:
 - * Better trigger, lepton-ID
 - * Better b-tagging
 - * Multiple topologies
 - * Multiple Higgs signatures
 - * MVA techniques
- Validation of techniques with expected signals

CDF Sensitivity vs Time



⇒ Sensitivity increase better than $\sqrt{\int \mathcal{L} dt}$

Higgs at Low Mass: $WH/ZH, H \rightarrow b\bar{b}$



- $W \rightarrow l\nu$: one lepton + \cancel{E}_T $Z \rightarrow ll$: two leptons
- $Z \rightarrow \nu\nu$: \cancel{E}_T
- $H \rightarrow b\bar{b}$: at least two jets, at least one b-tag
- Background sources:
 - * W/Z with additional jets (including $Wb\bar{b}$, $Zb\bar{b}$)
 - * $t\bar{t}$, single top
 - * Di-boson (WW , WZ , ZZ)
 - * Multi-jet production with mis-ID of lepton / \cancel{E}_T

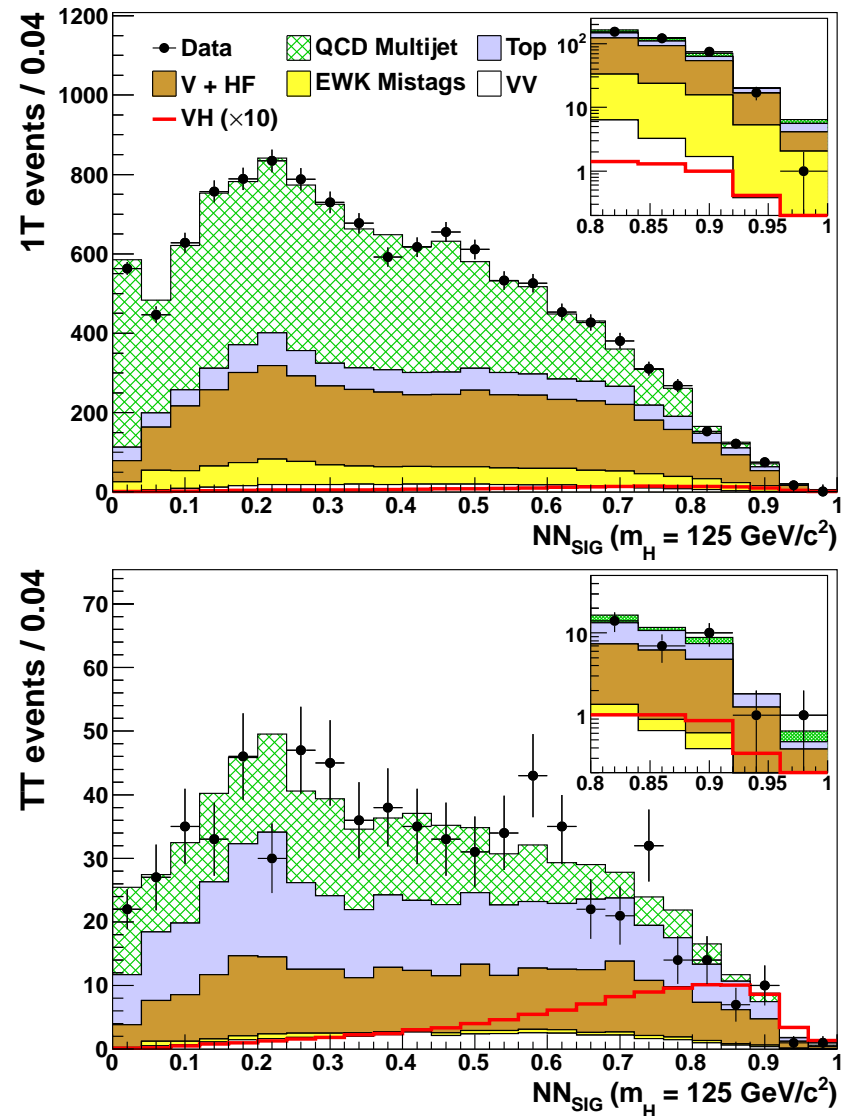
ZH $\rightarrow \nu\nu b\bar{b}$ (CDF)

$$\sigma \times \text{Br}(p\bar{p} \rightarrow \text{ZH} \rightarrow \nu\nu b\bar{b}) \simeq \sigma \times \text{Br}(p\bar{p} \rightarrow \text{WH} \rightarrow e/\mu\nu b\bar{b})$$

- Include $\text{WH} \rightarrow \ell\nu b\bar{b}$
- Two or three jets, include τ_h
- Three b-tag categories
- HOBIT[†] b-tagging \rightarrow 14% better sensitivity
- MVA techniques

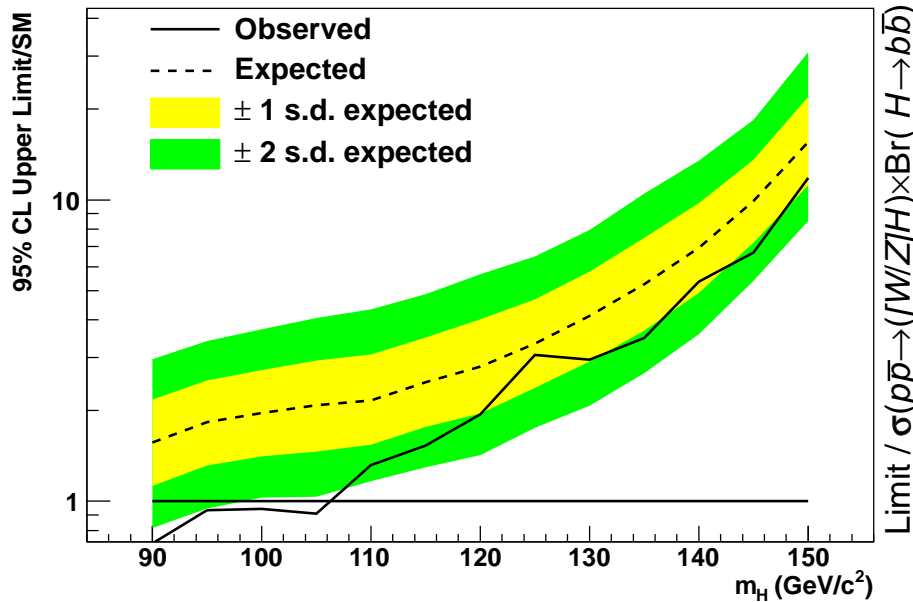
[†] Higgs Optimized b Identification Tagger

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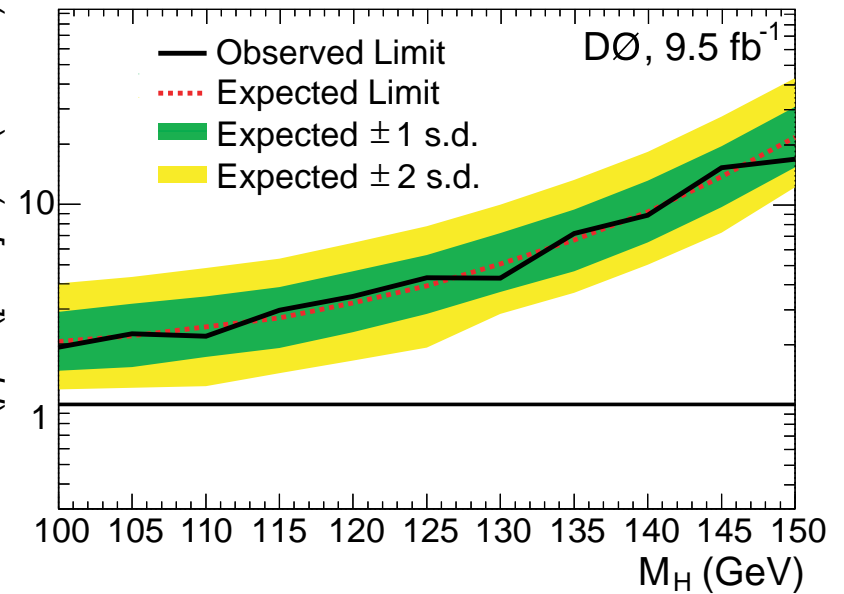
ZH $\rightarrow \nu\nu b\bar{b}$ (CDF,DØ)

CDF, $\int \mathcal{L} dt = 9.5 \text{ fb}^{-1}$



limit/SM 3.1 (3.3 exp.)
 @ $m_H = 125 \text{ GeV}$

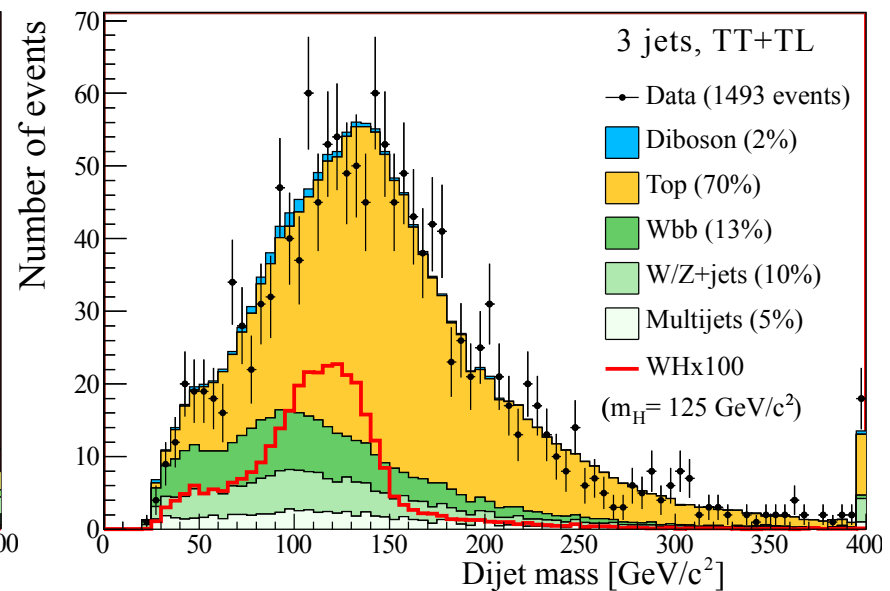
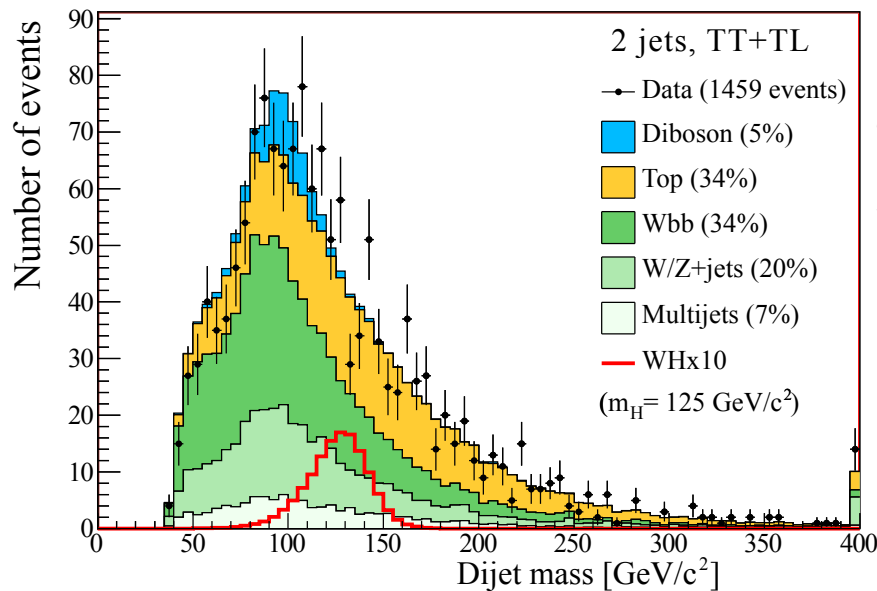
DØ, $\int \mathcal{L} dt = 9.5 \text{ fb}^{-1}$



limit/SM 4.3 (3.9 exp.)
 @ $m_H = 125 \text{ GeV}$

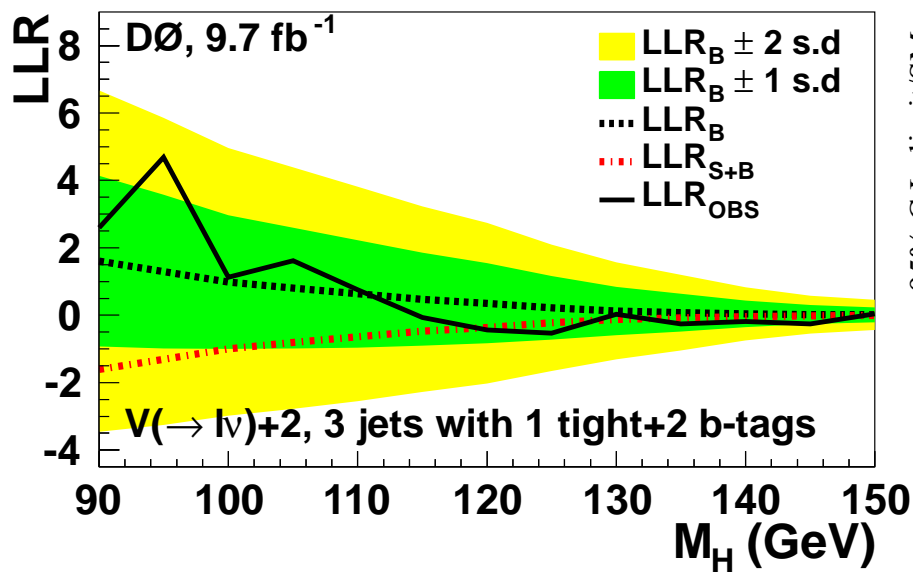
$WH \rightarrow \ell\nu b\bar{b}$ (CDF)

- Include “isolated track” as lepton candidate
- HOBIT b-tagging:
 - * Two jets: TT, TL, T, LL, L tags
 - * Three jets: TT, TL tags
- MVA techniques



WH $\rightarrow \ell\nu b\bar{b}$ (CDF,DØ)

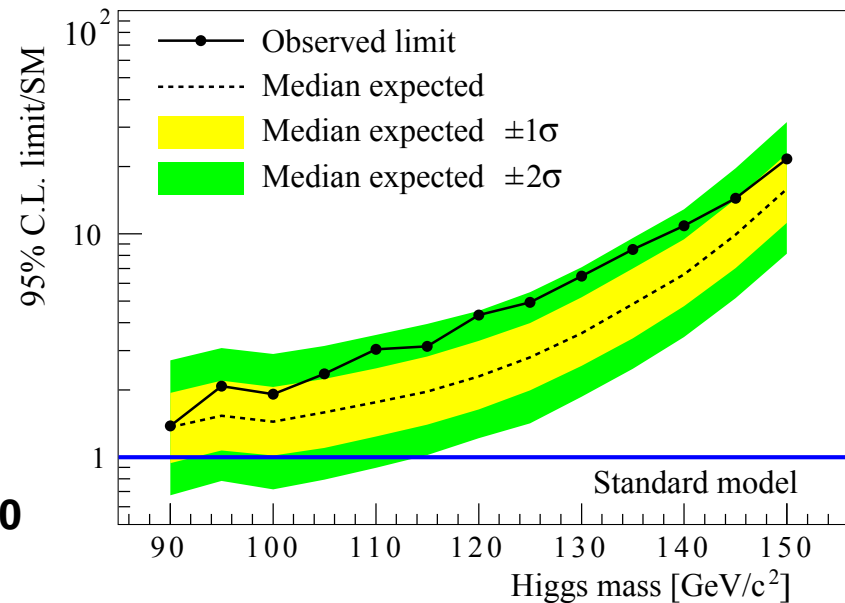
DØ, $\int \mathcal{L}dt = 9.7 \text{ fb}^{-1}$



limit/SM 4.8 (4.7 exp.)

@ $m_H = 125 \text{ GeV}$

CDF $\int \mathcal{L}dt = 9.5 \text{ fb}^{-1}$



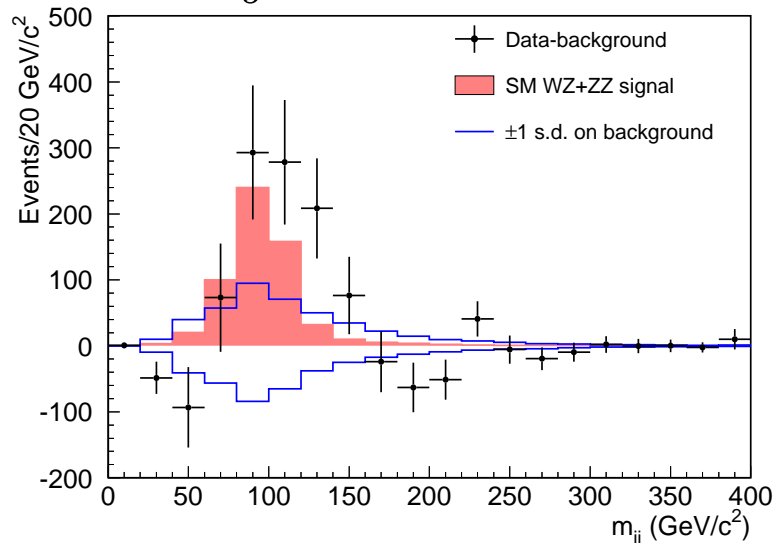
limit/SM 4.9 (2.8 exp.)

@ $m_H = 125 \text{ GeV}$

WZ/ZZ with $Z \rightarrow b\bar{b}$ (CDF,DØ)

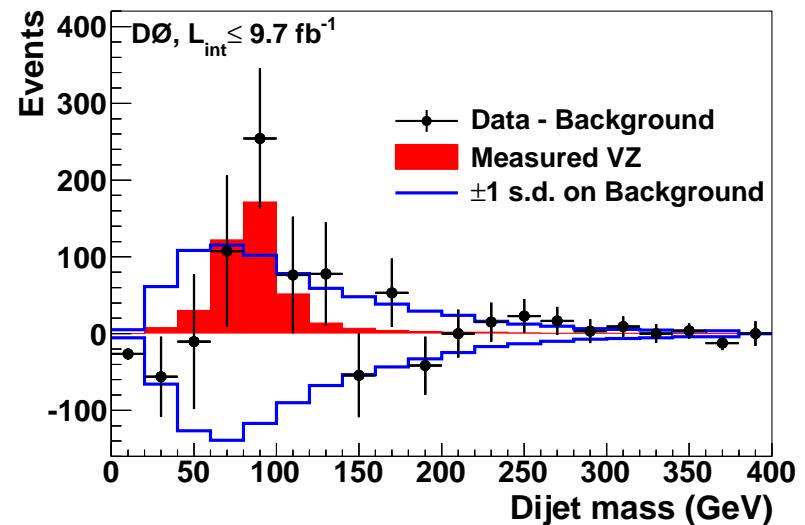
- Analyses identical to WH/ZH with $H \rightarrow b\bar{b}$
- Train MVA for $Z \rightarrow b\bar{b}$
- $\sigma(\text{WZ/ZZ}) \cdot \text{Br}(Z \rightarrow b\bar{b}) \simeq 5.5 \times \sigma(\text{WH/ZH}) \cdot \text{Br}(H \rightarrow b\bar{b})$

CDF, $\int \mathcal{L} dt = 9.5 \text{ fb}^{-1}$



$$\sigma(p\bar{p} \rightarrow VZ) = 2.6^{+1.3}_{-1.2} \text{ pb}$$

DØ, $\int \mathcal{L} dt \leq 9.7 \text{ fb}^{-1}$



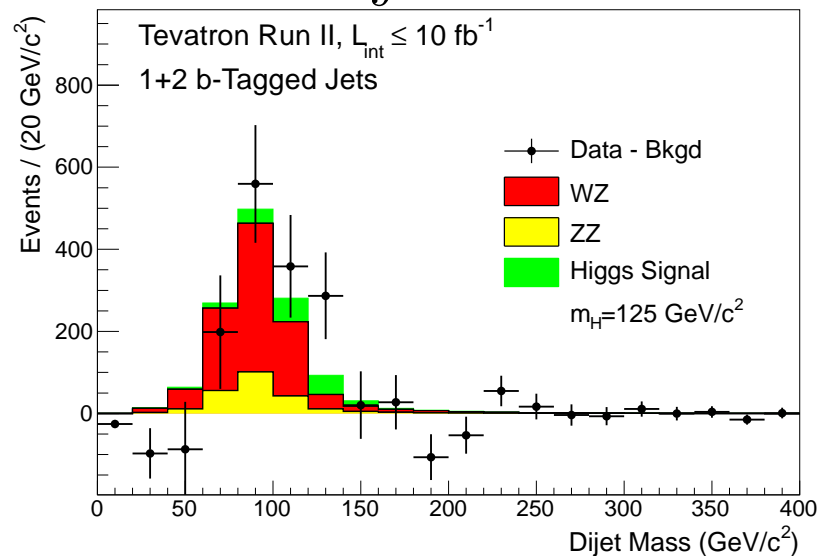
$$\sigma(p\bar{p} \rightarrow VZ) = 3.2 \pm 1.4 \text{ pb}$$

$$\sigma_{\text{SM}} = 4.4 \pm 0.3 \text{ pb}$$

WZ/ZZ with Z \rightarrow b \bar{b} (CDF,DØ)

- Analyses identical to WH/ZH with H \rightarrow b \bar{b}
- Train MVA for Z \rightarrow b \bar{b}
- $\sigma(\text{WZ/ZZ}) \cdot \text{Br}(Z \rightarrow \text{b}\bar{\text{b}}) \simeq 5.5 \times \sigma(\text{WH/ZH}) \cdot \text{Br}(H \rightarrow \text{b}\bar{\text{b}})$

CDF & DØ, $\int \mathcal{L} dt < 10 \text{ fb}^{-1}$

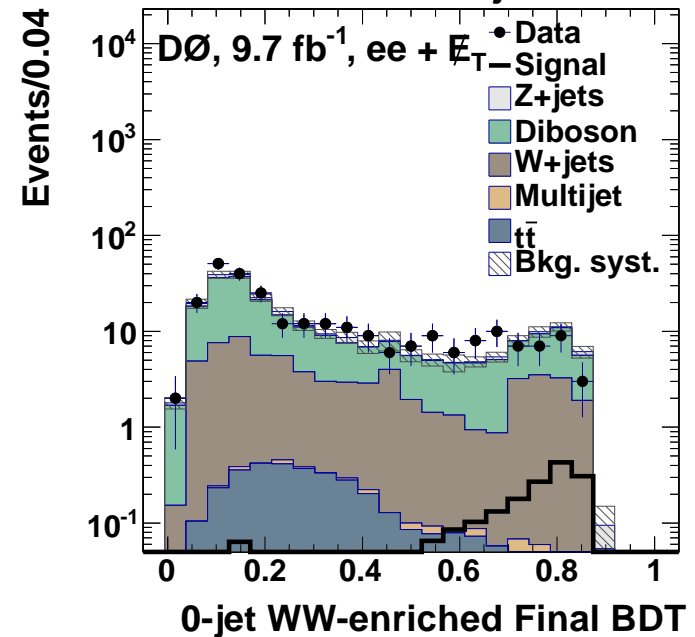
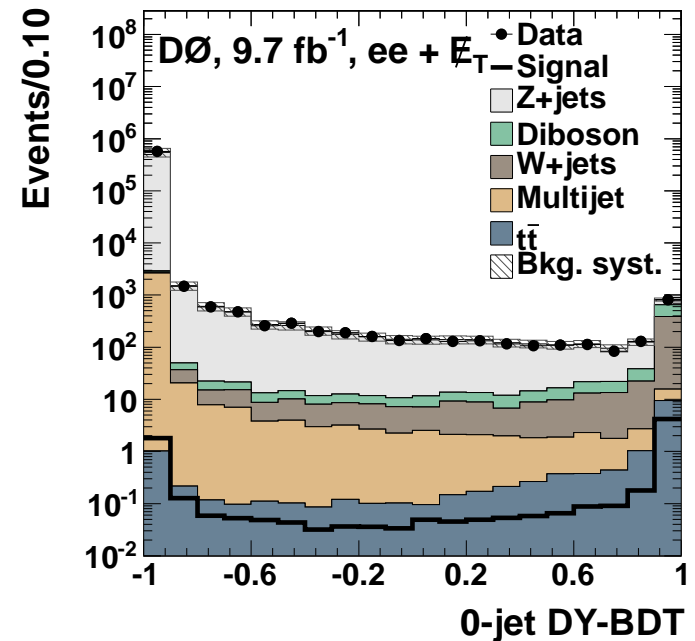


$$\sigma(\text{p}\bar{\text{p}} \rightarrow \text{VZ}) = 3.0 \pm 0.6(\text{stat}) \pm 0.7(\text{sys}) \text{ pb}$$

$$\sigma_{\text{SM}} = 4.4 \pm 0.3 \text{ pb}$$

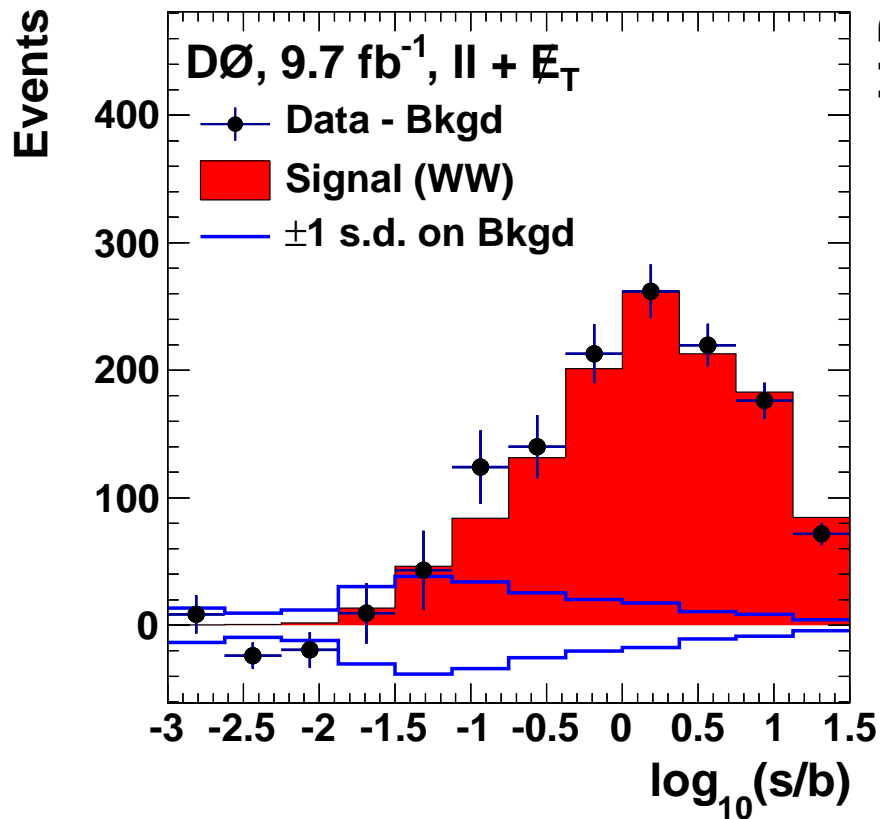
H \rightarrow WW (DØ)

- H \rightarrow WW \rightarrow $l\nu l\nu$
- Background sources:
 - * Di-boson (WW, WZ, ZZ)
 - * $t\bar{t}$, DY di-lepton production
 - * W + mis-identified jet/ γ
- Inclusive triggering
- No \cancel{E}_T cut / Z veto \rightarrow anti-DY BDT (ee, $\mu\mu$)
- WW enriched / depleted samples
- BDT for final signal identification



H → WW (DØ)

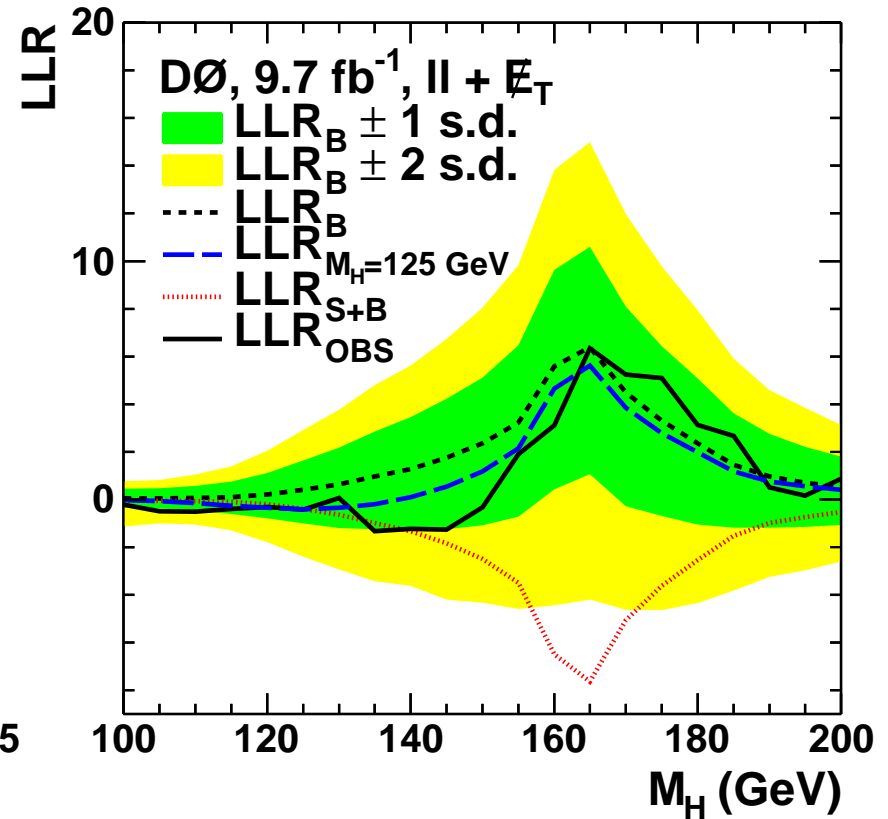
$\sigma(p\bar{p} \rightarrow WW)$ measurement



$$\sigma = 11.6 \pm 0.7(\text{stat} \oplus \text{sys}) \text{ pb}$$

$$\sigma_{\text{SM}} = 11.3 \pm 0.7 \text{ pb}$$

H → WW search



limit/SM 4.1 (3.4 exp.)

@ $m_H = 125 \text{ GeV}$

Exclude $159 < m_H < 176 \text{ GeV}$

Higgs at Low Mass: Summary

For $m_H = 125$ GeV

	DØ		CDF	
	$\int \mathcal{L} dt$	limit (exp.)	$\int \mathcal{L} dt$	limit (exp.)
$WH \rightarrow \ell \nu b \bar{b}$	9.7	4.8 (4.7)	9.5	4.9 (2.8)
$ZH \rightarrow \ell \ell b \bar{b}$	9.7	7.1 (5.1)	9.5	7.1 (3.9)
$ZH \rightarrow \nu \nu b \bar{b}$	9.5	4.3 (3.9)	9.5	3.1 (3.3)
$H \rightarrow WW^\dagger$	9.7	4.1 (3.4)	9.7	3.0 (3.1)
$H \rightarrow \tau\tau$	9.7	12.8 (10.4)	6.0	14.6 (15.3)
$H \rightarrow \gamma\gamma$	9.6	12.8 (8.7)	10.0	17.0 (9.9)

\Rightarrow Combine search channels

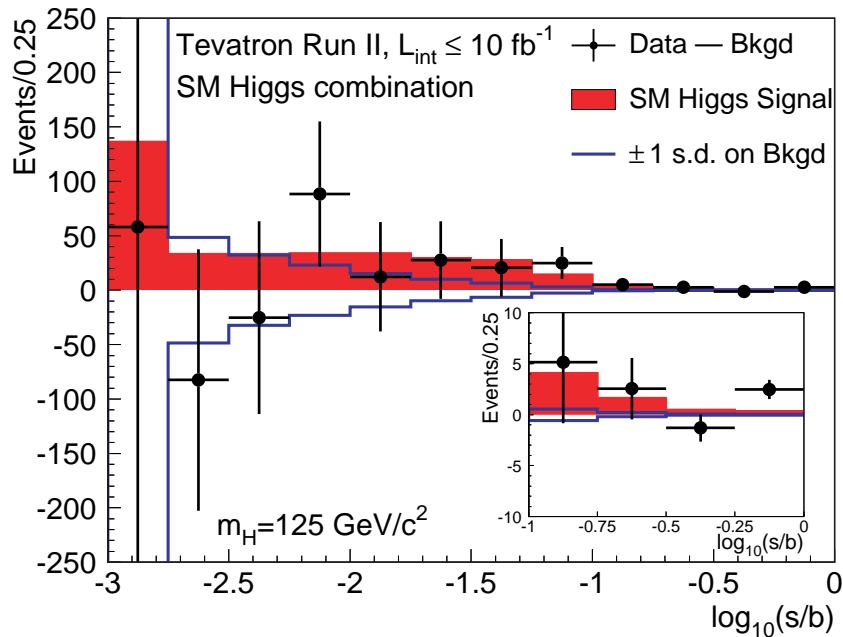
† CDF / DØ not same final states

Tevatron Higgs Combination

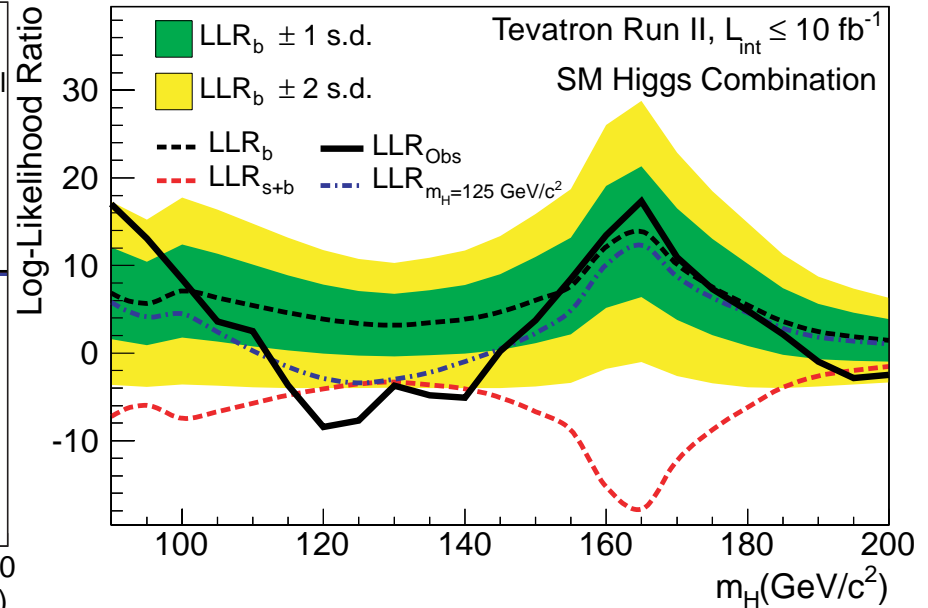
$$H \rightarrow b\bar{b}, H \rightarrow WW, H \rightarrow ZZ, H \rightarrow \tau\tau, H \rightarrow \gamma\gamma$$

More than 100 analysis channels

Data, background subtracted

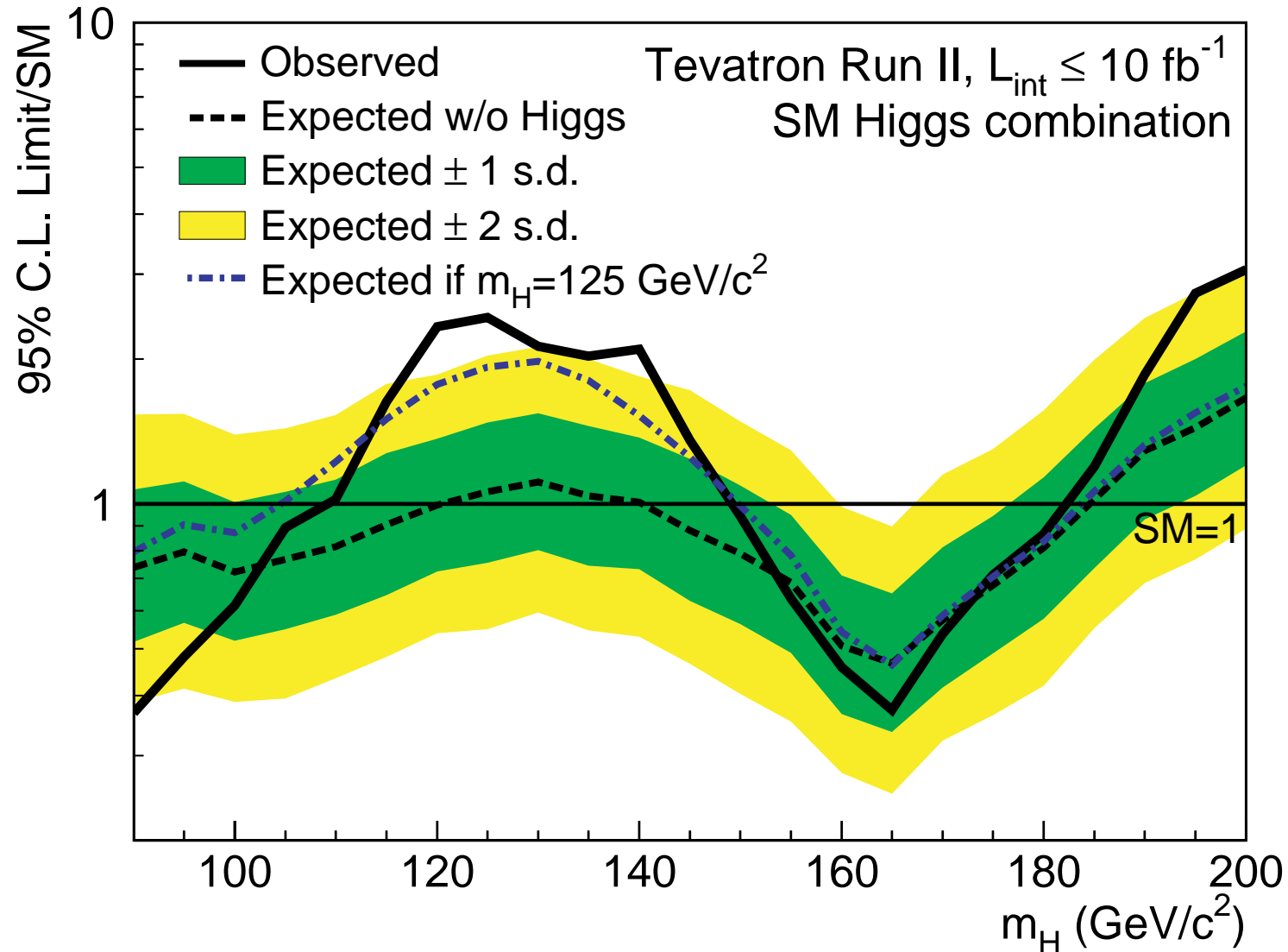


Likelihood ratio



Excess ($> 2\sigma$) for $115 < m_H < 140 \text{ GeV}$

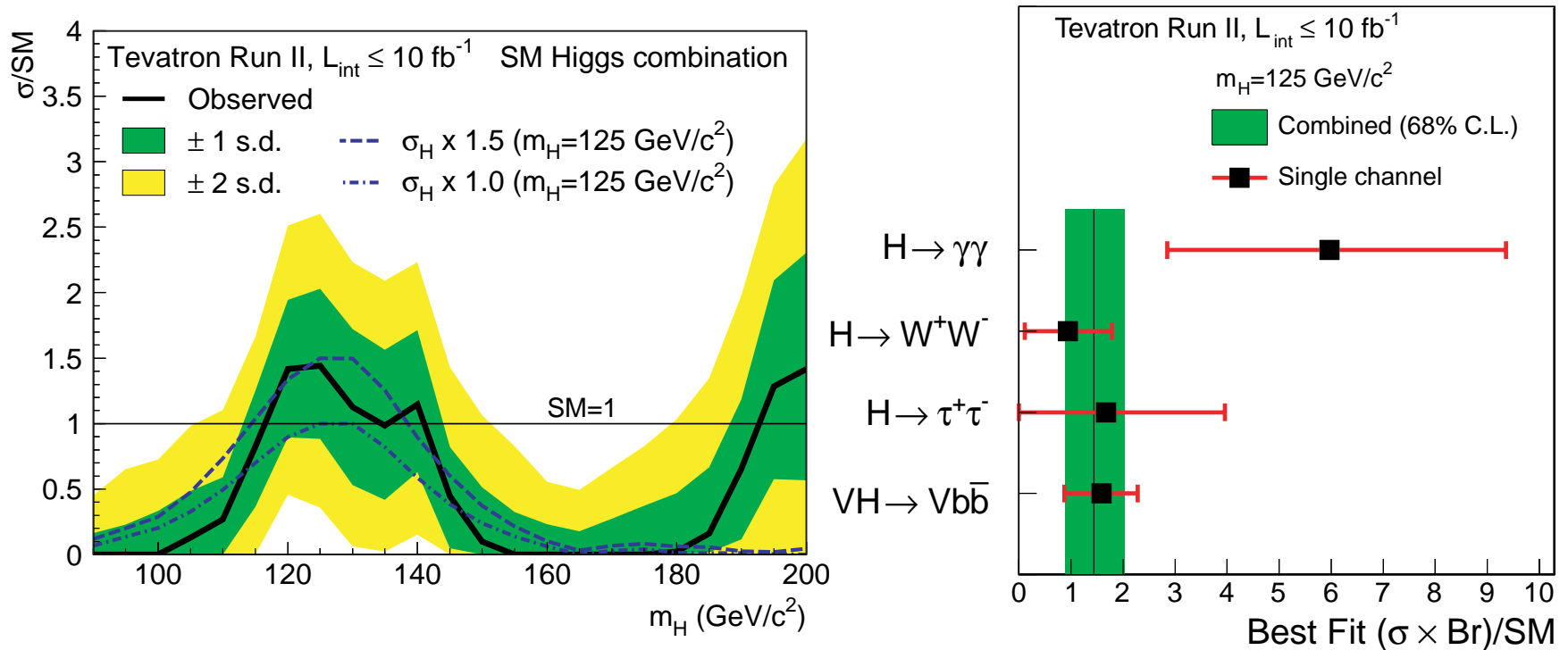
Tevatron Higgs Combination



Exclude $90 < m_H < 109 \text{ GeV}$, $149 < m_H < 182 \text{ GeV}$

Tevatron Higgs Combination

Higgs cross-section measurement

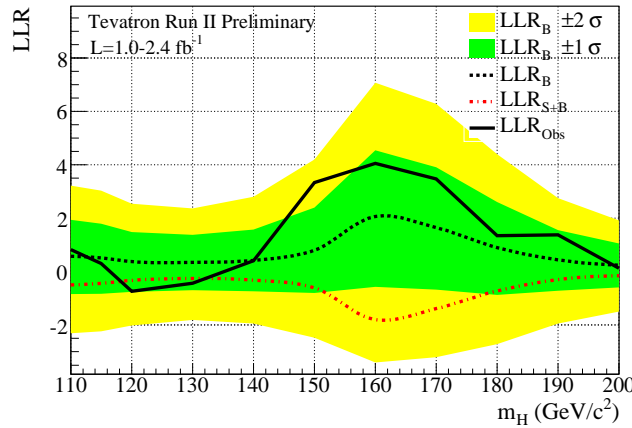


$$\sigma/\sigma_{\text{SM}} = 1.44^{+0.59}_{-0.56} @ m_H = 125 \text{ GeV}$$

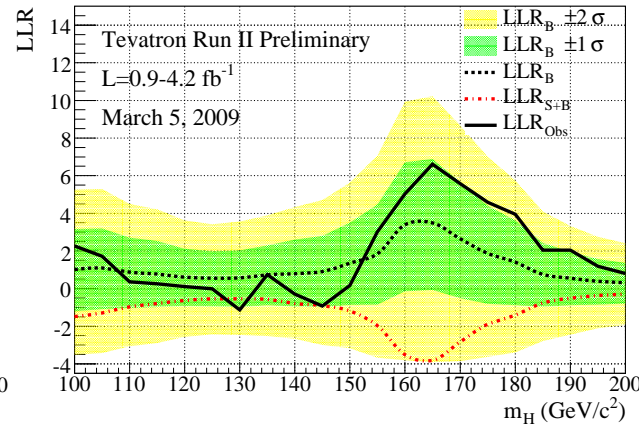
3.1 σ excess

Higgs @ Tevatron Search History

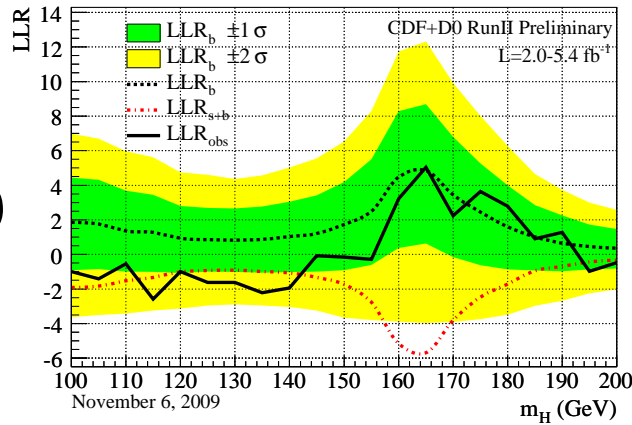
4/2008



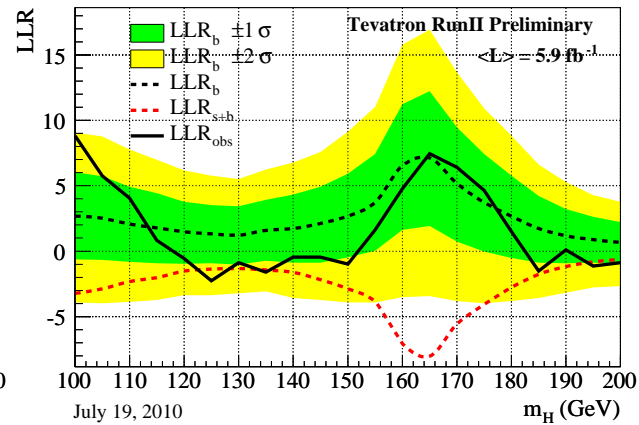
3/2009



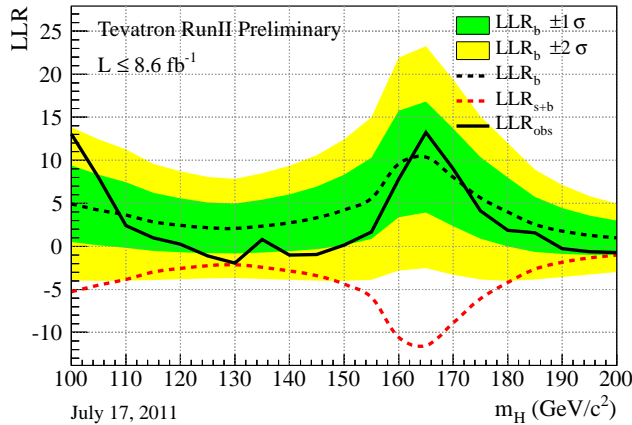
11/2009



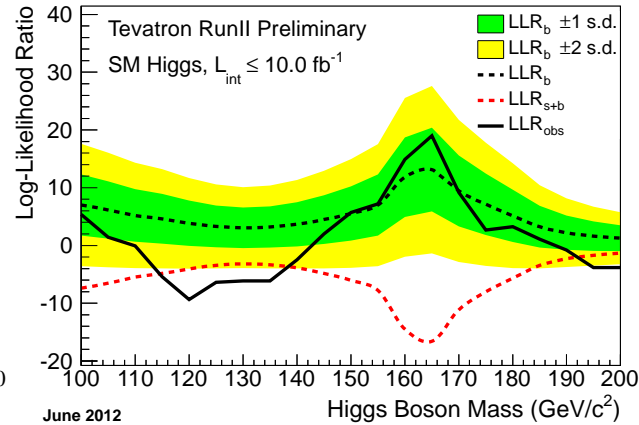
7/2010



7/2011



6/2012

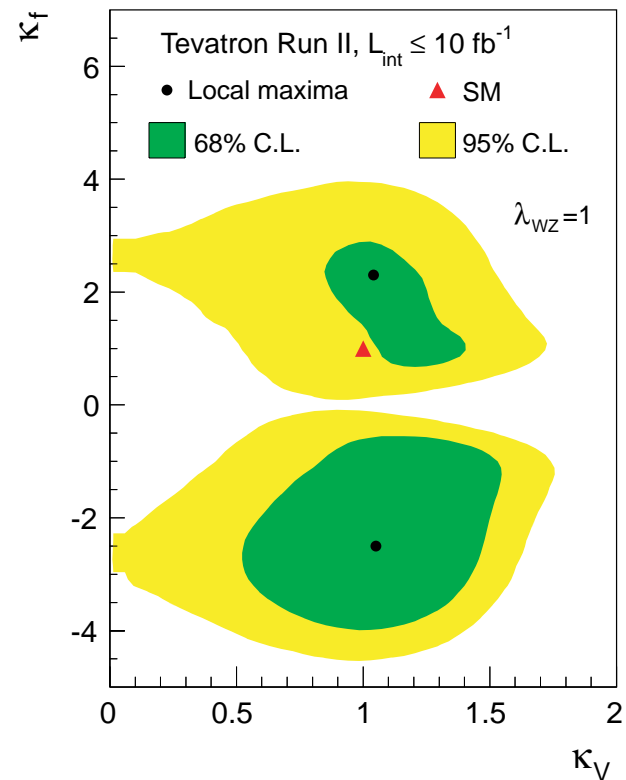
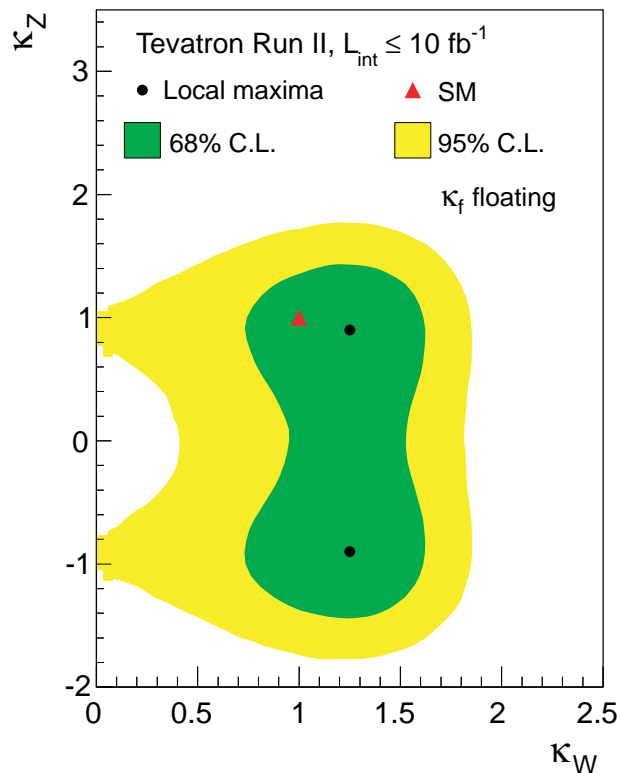


Higgs Couplings

– Production & decay: mixture of Hff, HWW, HZZ couplings

⇒ Probe scale factors $\kappa_f, \kappa_W, \kappa_Z$ (κ_V)

– E.g. $\Gamma(H \rightarrow \gamma\gamma) = \Gamma(H \rightarrow \gamma\gamma)_{\text{SM}} \times |1.28 \kappa_V - 0.28 \kappa_f|^2$

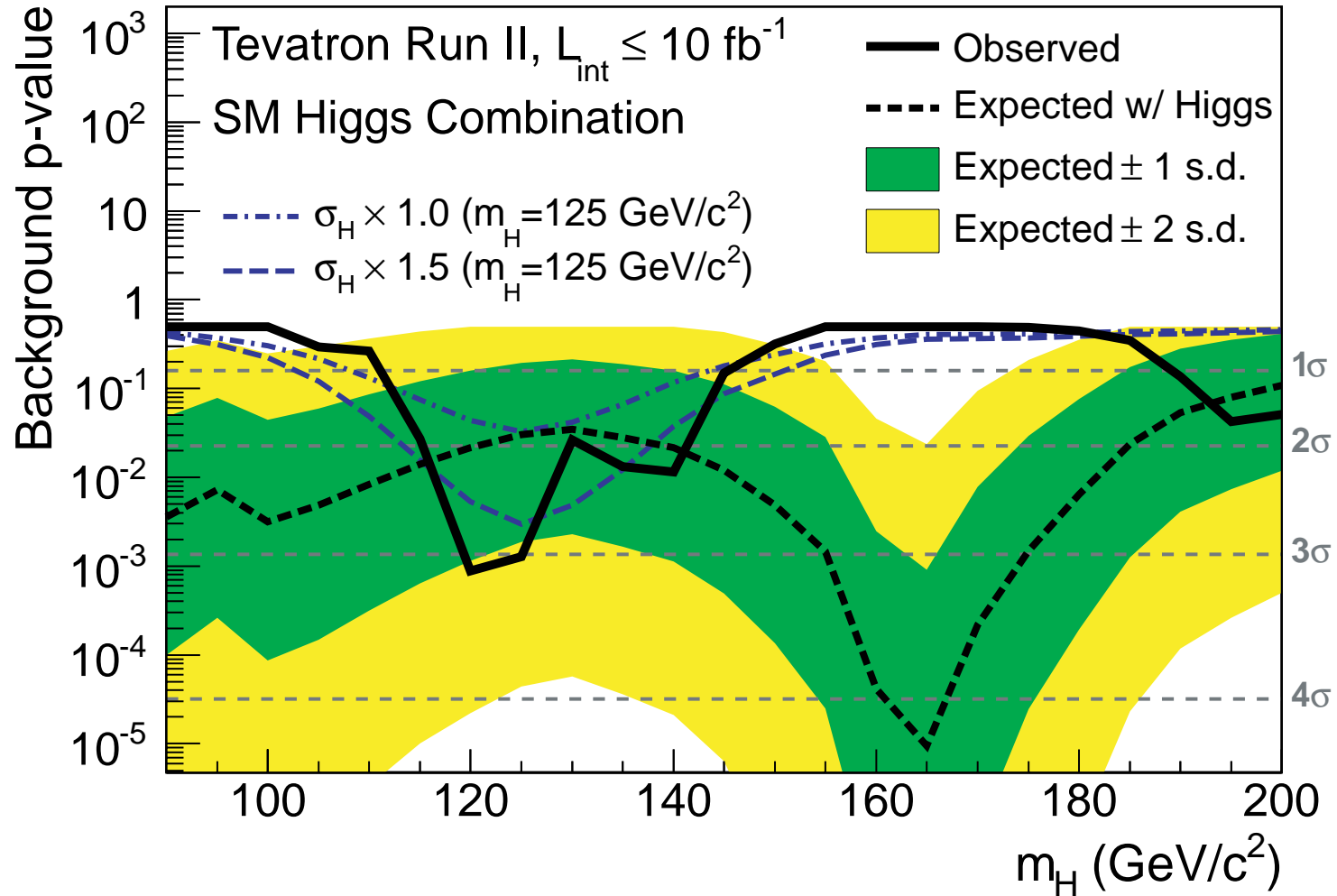


⇒ Consistent with SM Higgs

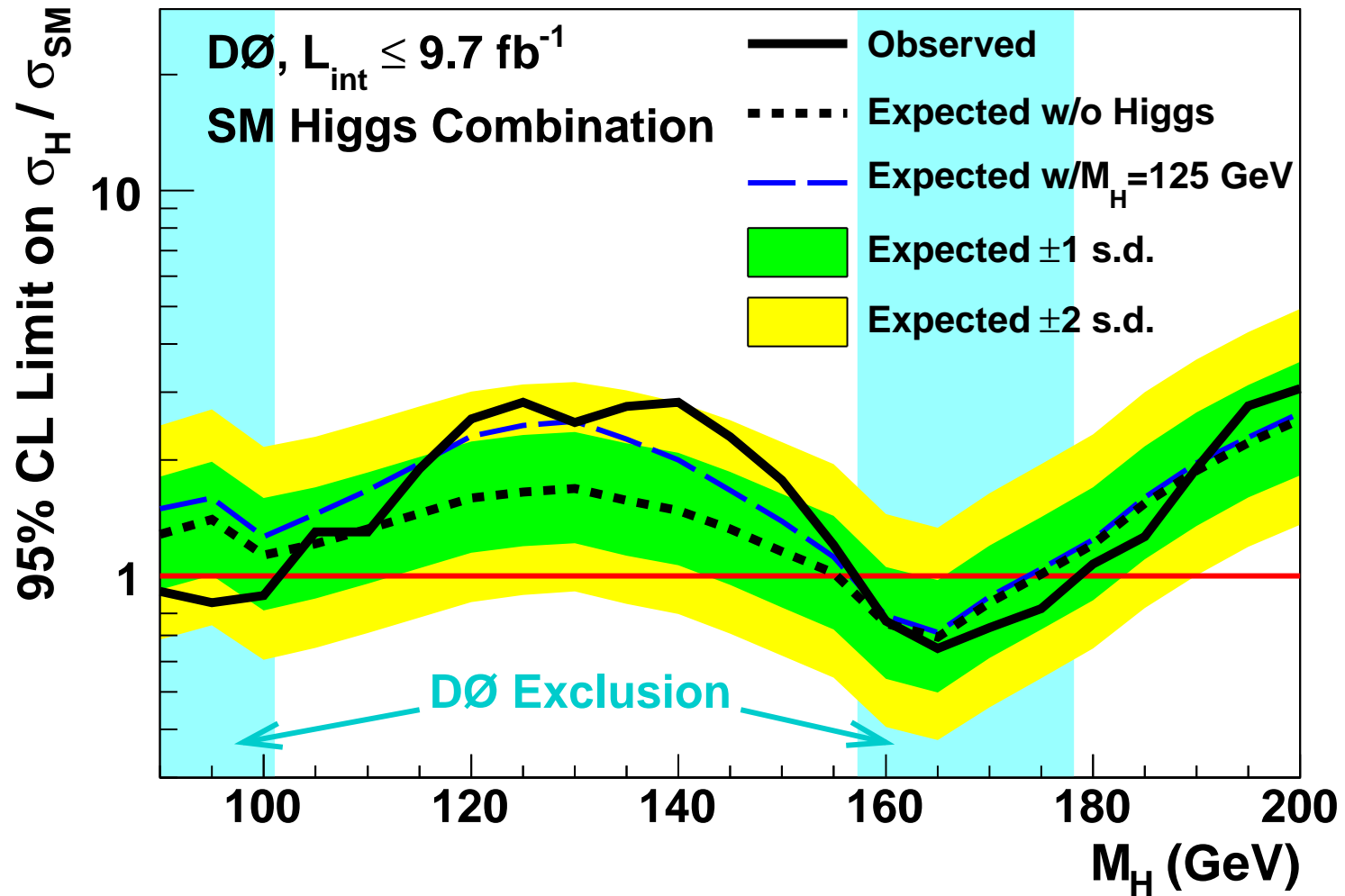
Conclusion

- Higgs-like excess observed around $m_H = 125$ GeV, 3.1σ
- Driven by $H \rightarrow b\bar{b}$ and $H \rightarrow WW$
- Consistent with SM Higgs
- Complementary to LHC results
- More details:
 - * DØ combination: [arXiv:1303.0823](https://arxiv.org/abs/1303.0823) (PRD)
 - * CDF combination: [arXiv:1301.6668](https://arxiv.org/abs/1301.6668) (PRD)
 - * Tevatron combination: [arXiv:1303.6346](https://arxiv.org/abs/1303.6346) (PRD)
 - * Tevatron Higgs group: <http://tevnphwg.fnal.gov>

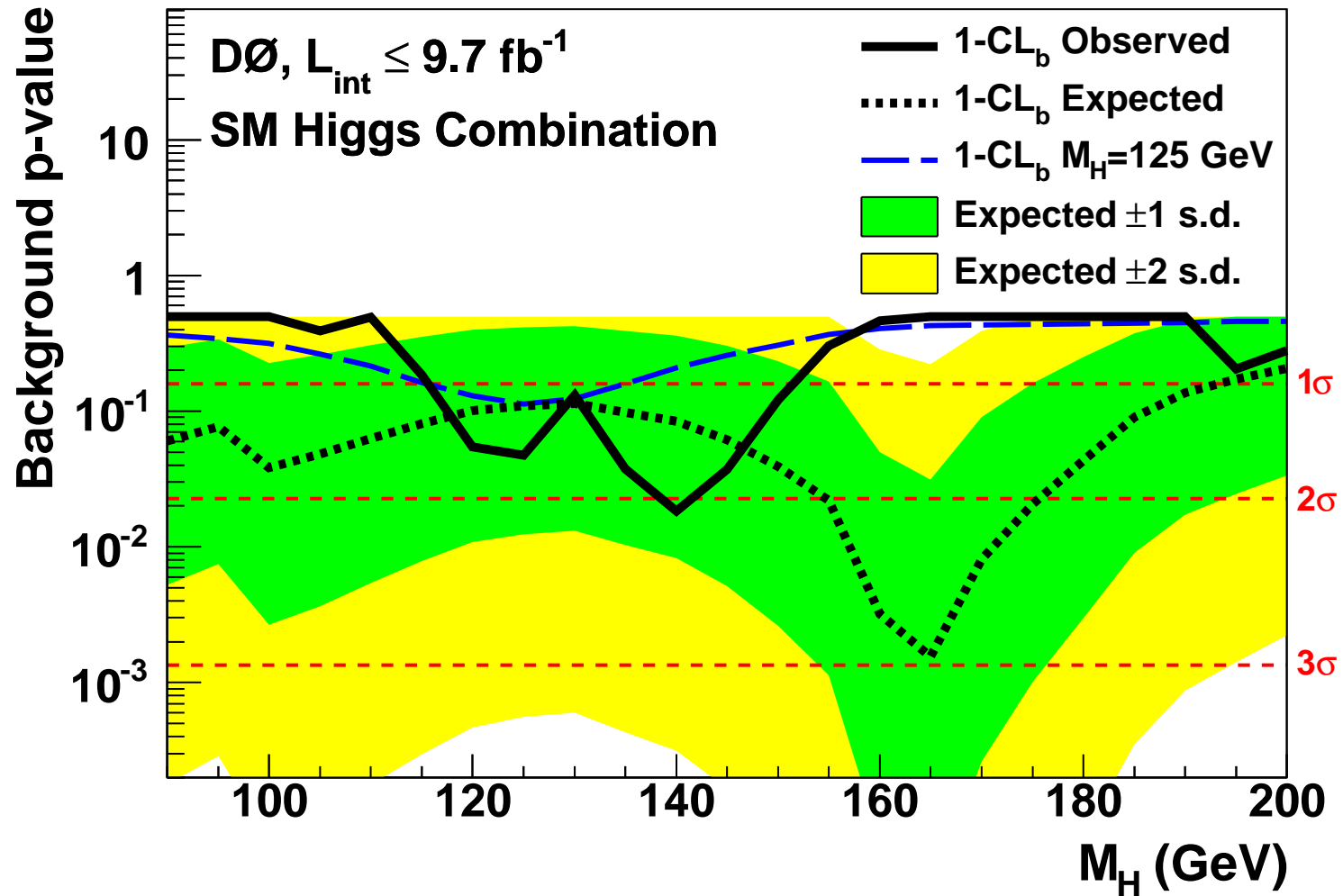
Tevatron Higgs Combination



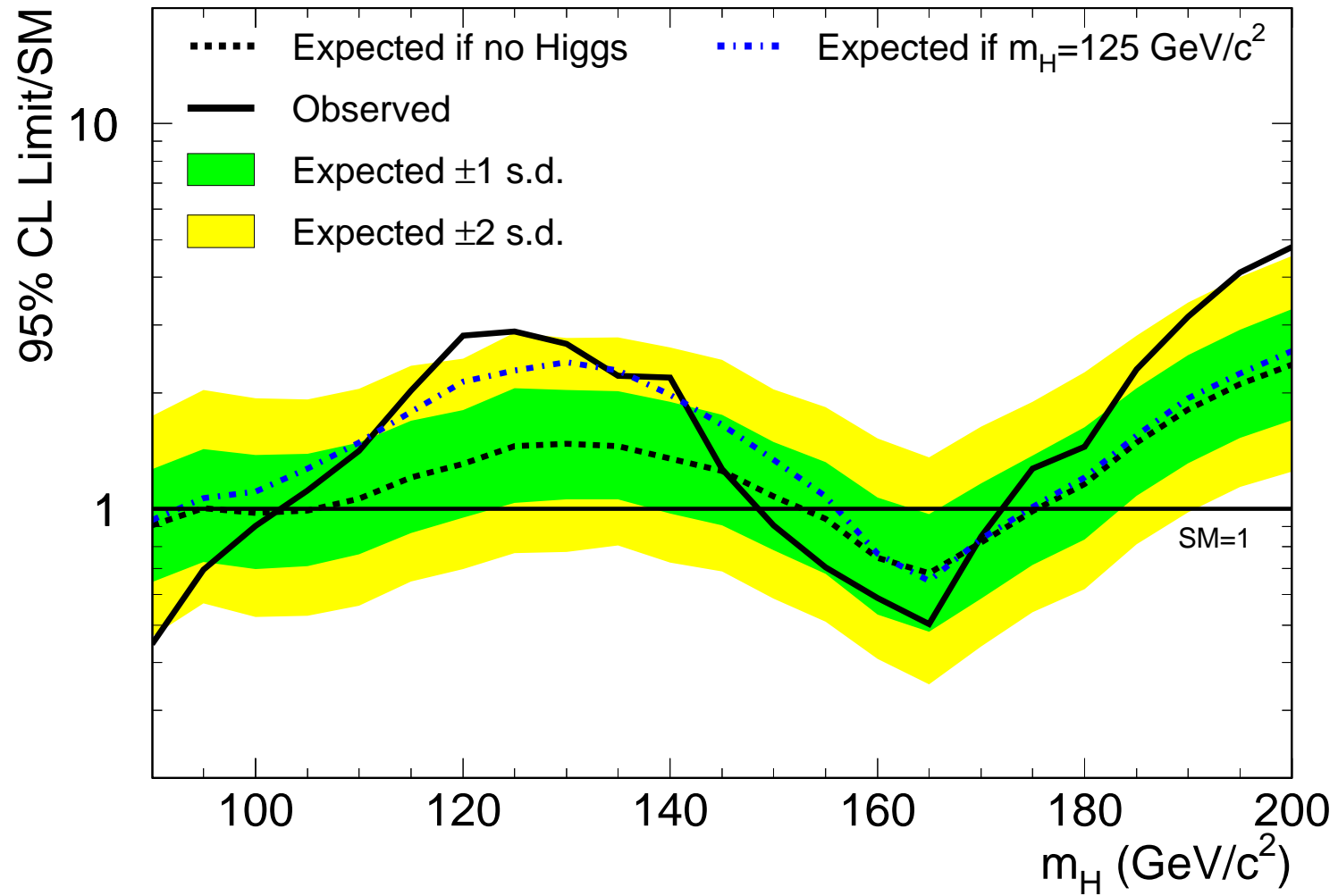
Higgs Combination (DØ)



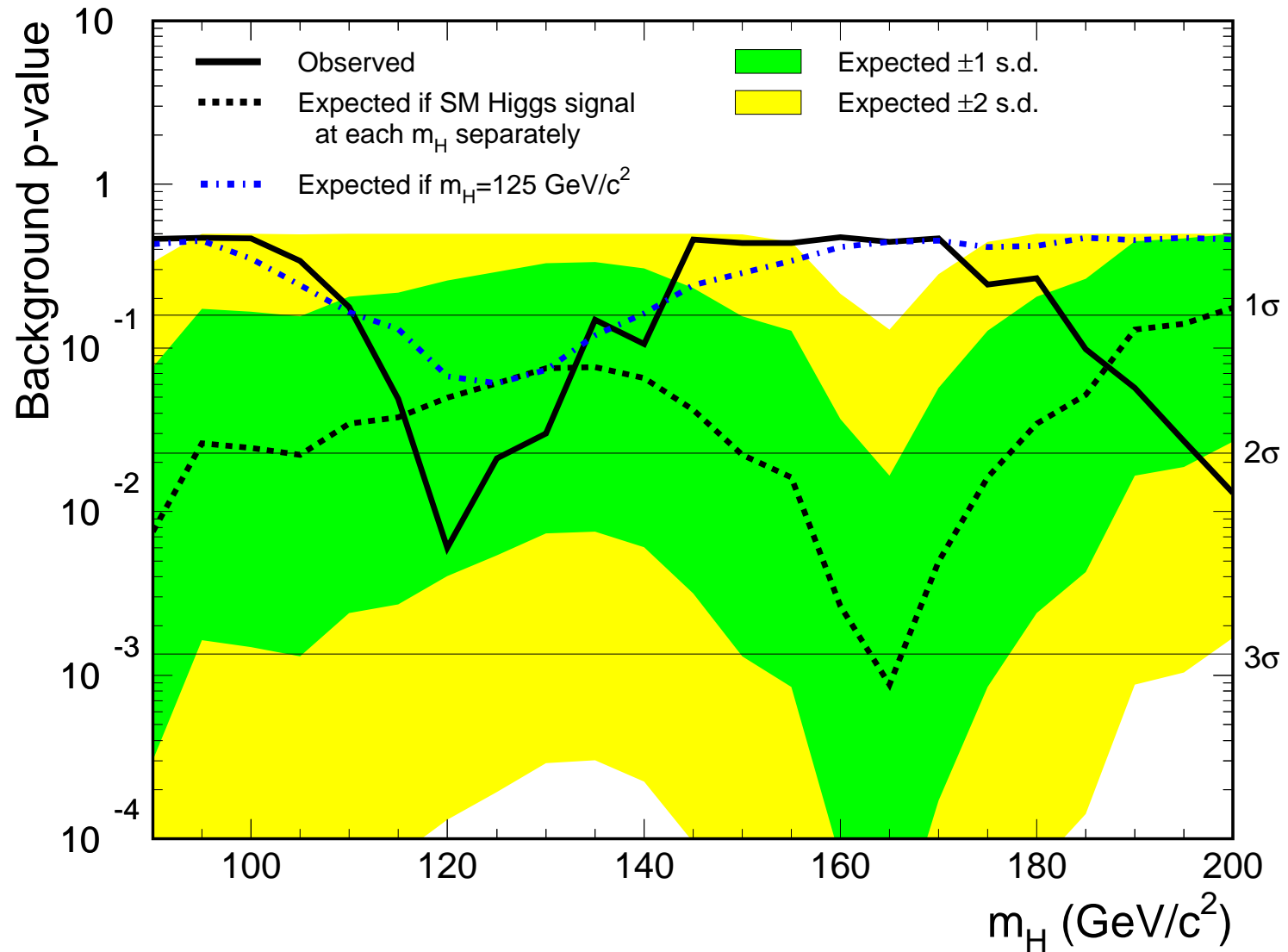
Higgs Combination (DØ)



Higgs Combination (CDF)



Higgs Combination (CDF)

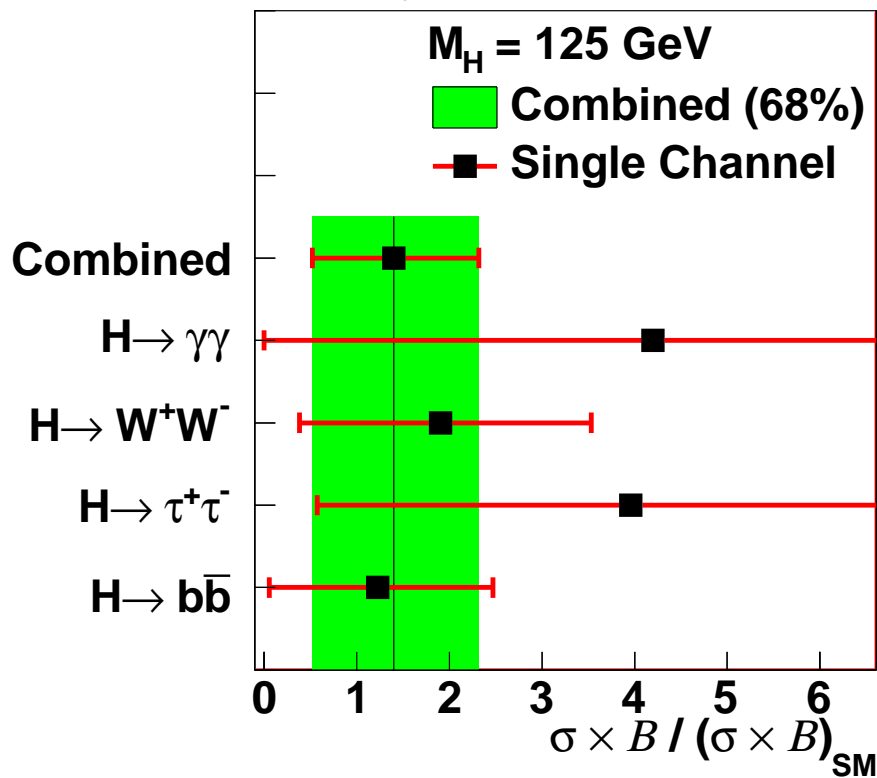


Higgs Cross-section (CDF,DØ)

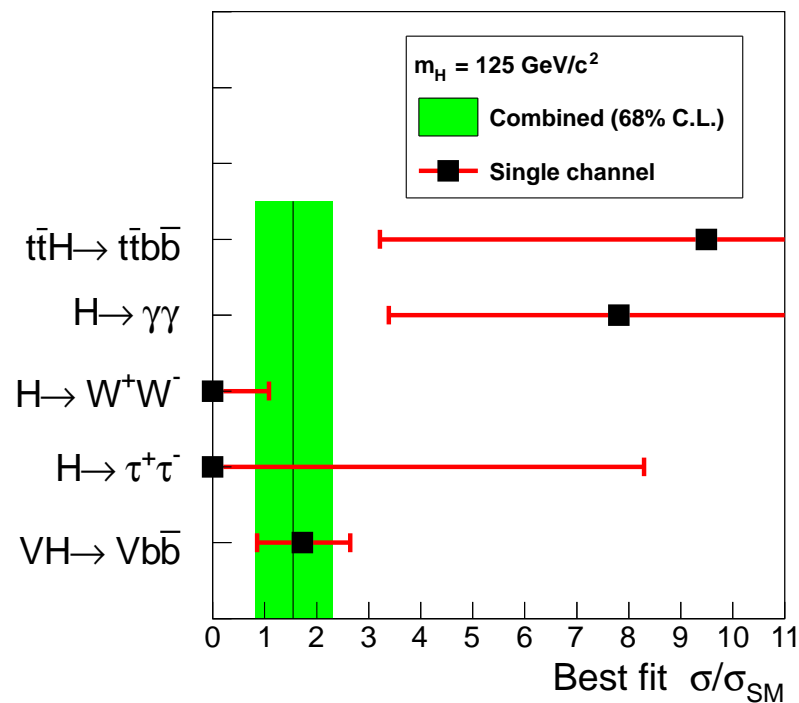
DØ

CDF

DØ, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$



$$\sigma/\sigma_{\text{SM}} = 1.40^{+0.92}_{-0.88}$$



$$\sigma/\sigma_{\text{SM}} = 1.54^{+0.77}_{-0.73}$$

b-Tagging

