Higgs Boson Studies at the Tevatron in Run II

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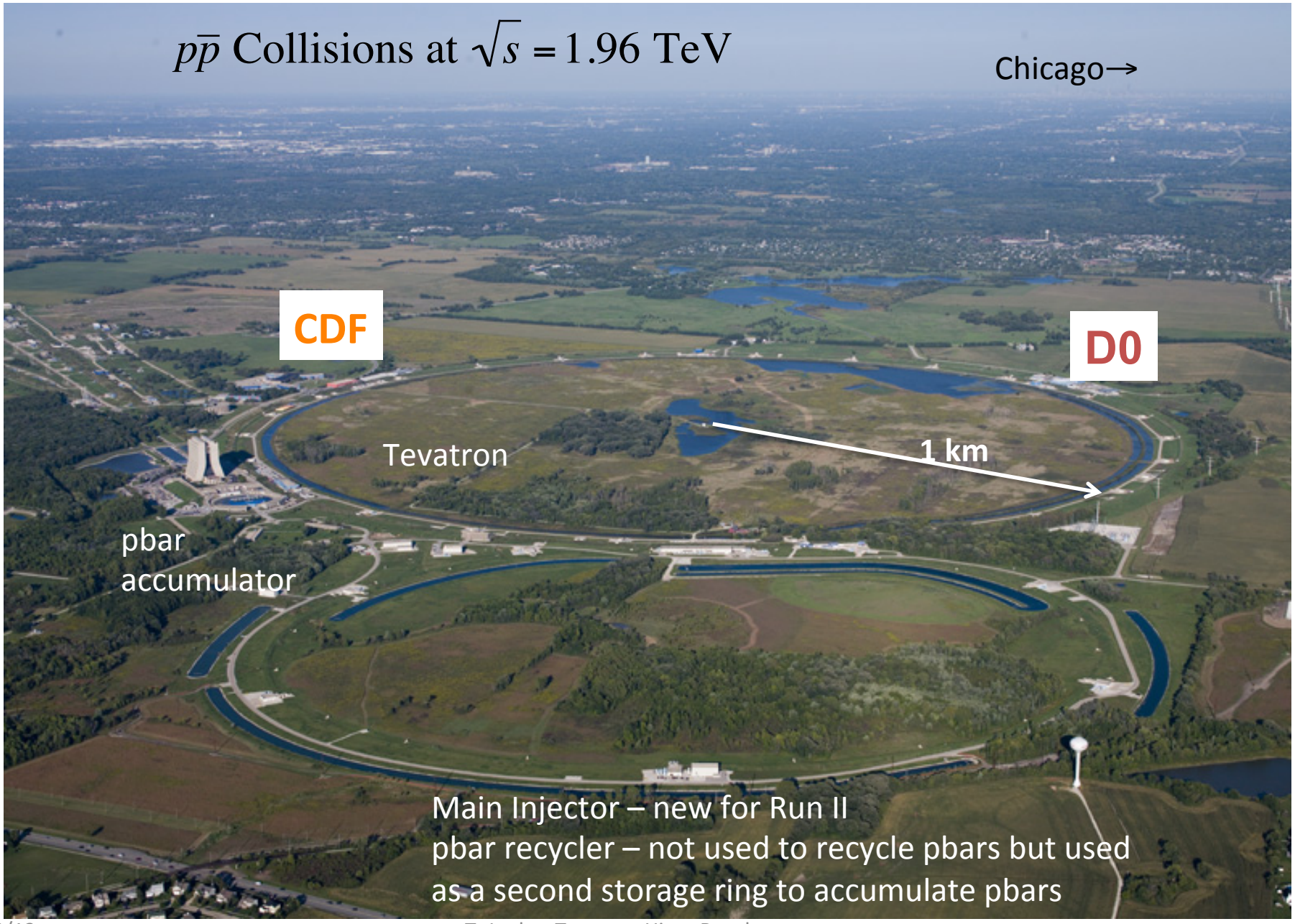
Fermilab
On Behalf of the CDF and D0 Collaborations

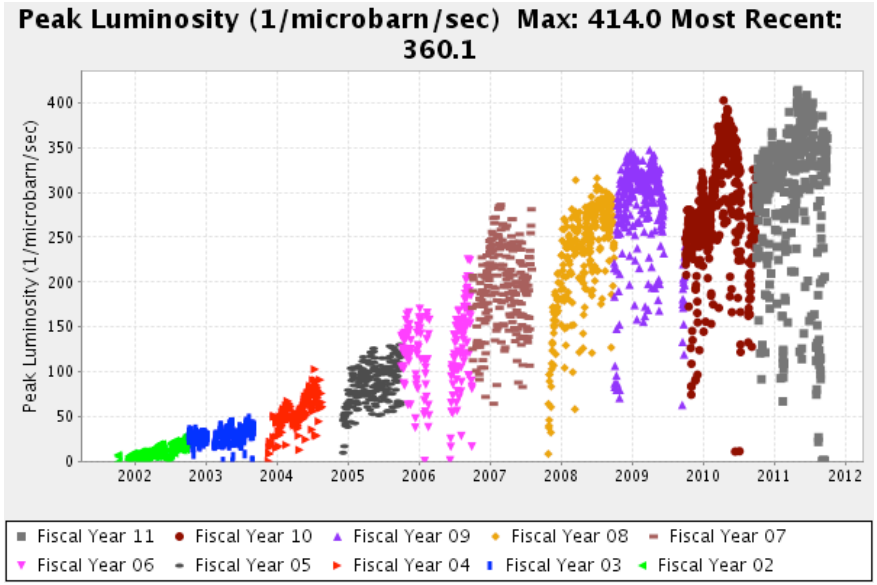
APS April Meeting, Denver, CO
April 14, 2013

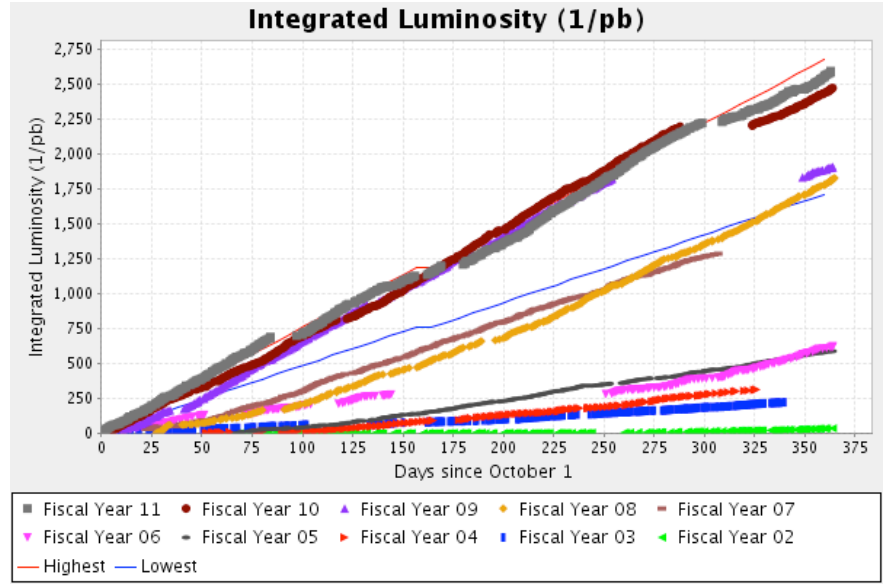
- The Tevatron, CDF, and D0
- Higgs Boson Production and Decay
- Highlights of Search Techniques – What we Learned
- Results: Limits, Cross Sections, Significance
- Results: Couplings, BSM models

Fermilab from the Air

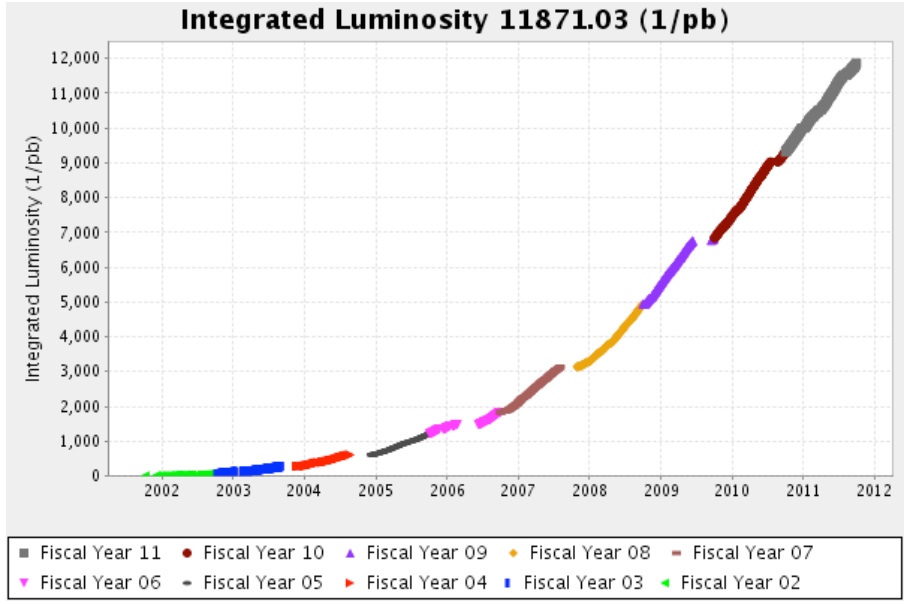


The Tevatron, Like All Accelerators, Improved in Performance Over Time





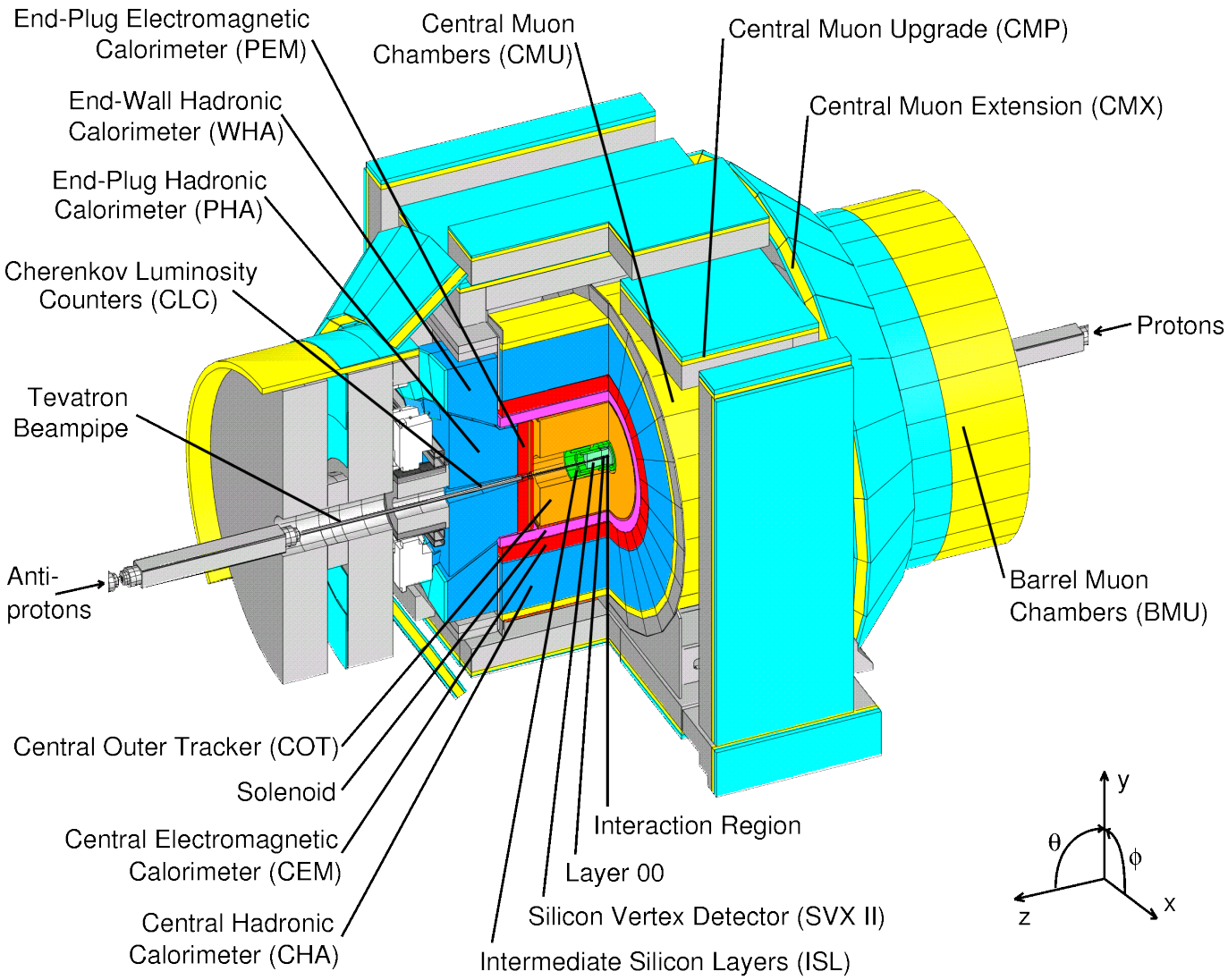
Many thanks to the Fermilab Beams Division!



Total delivered luminosity:
~12 fb^{-1} each to CDF and D0.

Acquired and analyzed:
~10 fb^{-1} each.

First CDF pp event: 1985
End of operations: 2011



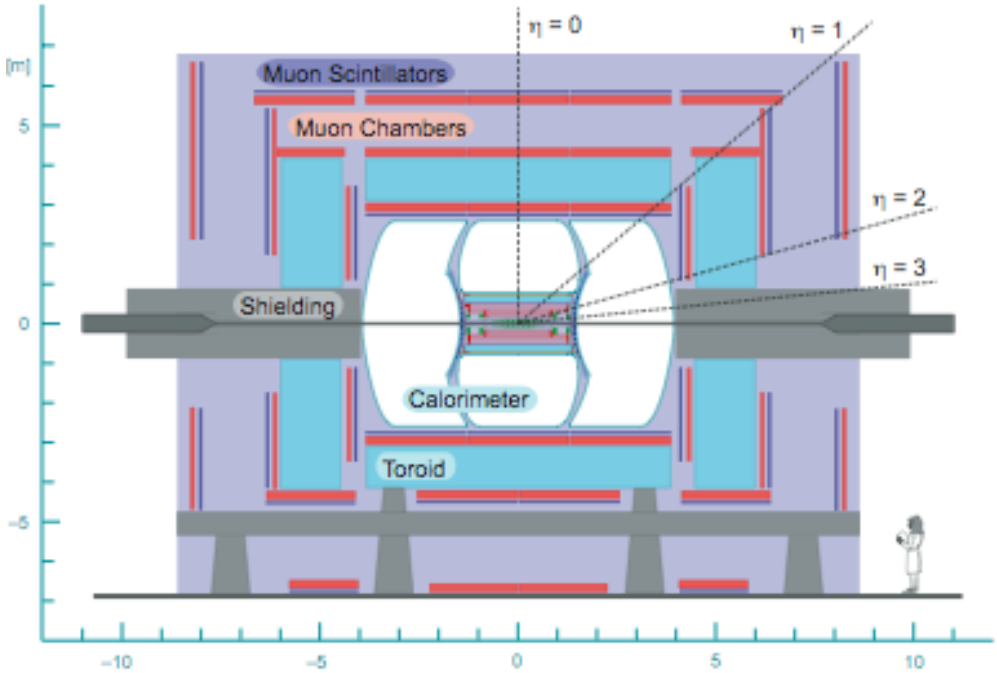
Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

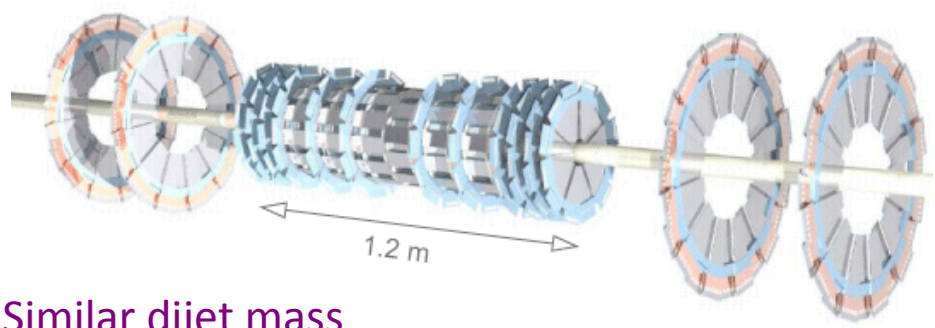
b-tagging with
$|\eta| < \sim 1.4$

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

Dijet mass resolution: ~16%

The DØ Detector





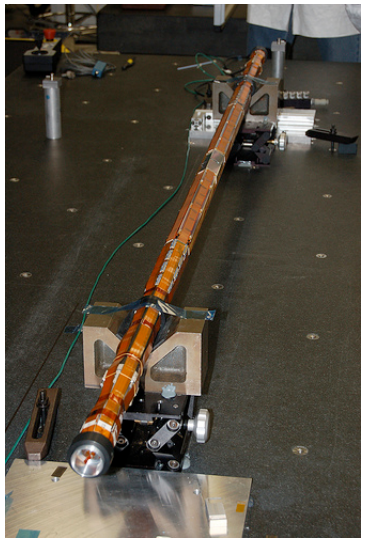
Lepton coverage:
|η| < 2 (muons)
|η| < 2.6 (electrons)

b-tagging with
|η| < ~2

Jets to
|η| < 3

Scintillating fiber tracker

Trigger similar to CDF's

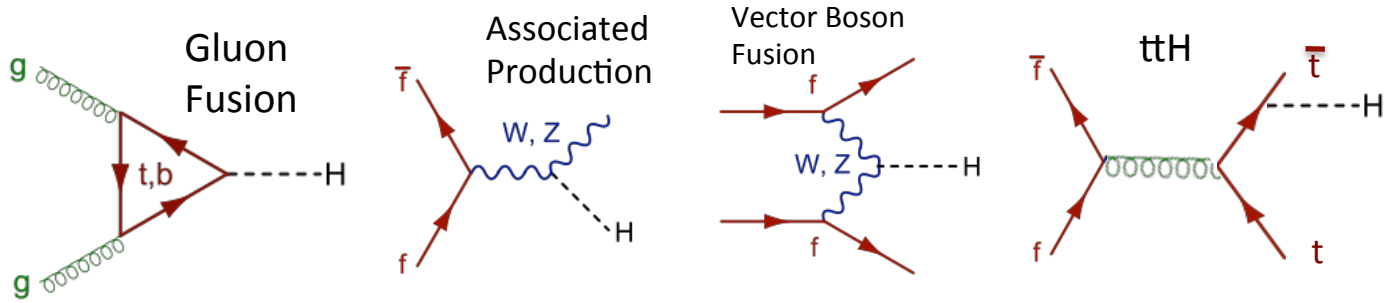


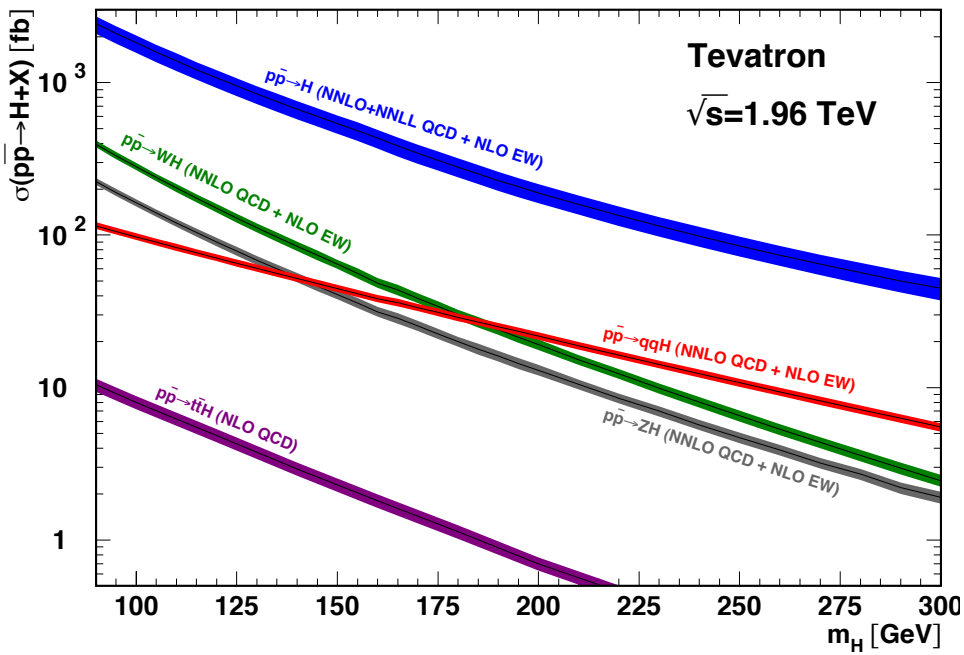
Similar dijet mass resolution to CDF

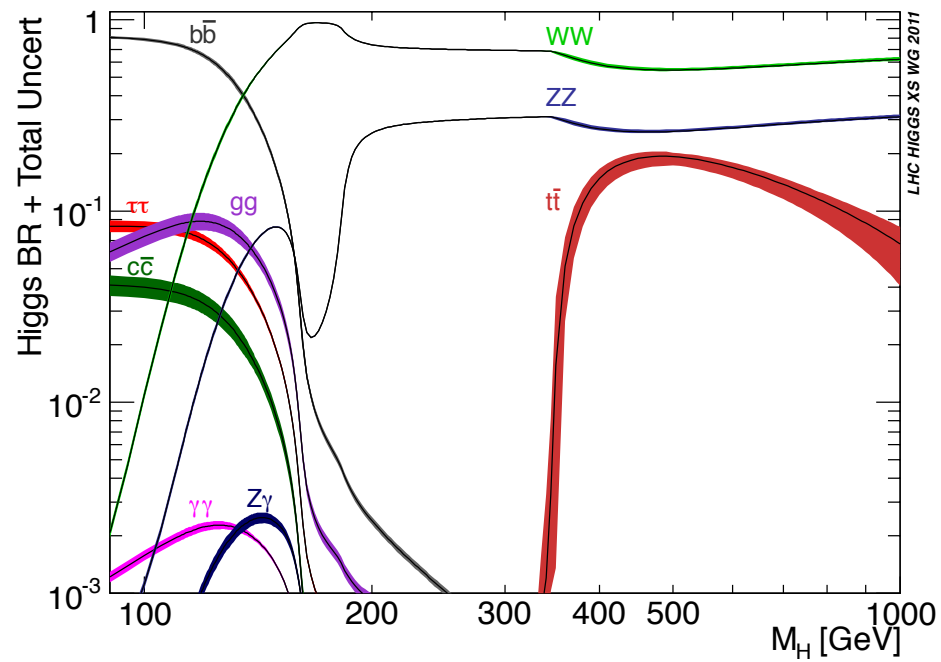
Good Feature: Regular Switching of Solenoid Field – Cancels Some Systematic Uncertainties

New Innermost Silicon Layer added between Run IIa and Run IIb

SM Higgs Boson Production and Decay Rates







Primary analysis modes:

m_H<130 GeV: VH→Vbb
m_H>130 GeV: gg→H→WW

Additional modes:

H→ττ, H→γγ, H→ZZ→4l

Tevatron H→bb Publications, Summer 2012

CDF, D0, and Tevatron Publications:

CDF lvbb:	Phys. Rev. Lett. **109**, 111804 (2012)	Includes new HOBIT b-tagger
CDF llbb:	Phys. Rev. Lett. **109**, 111803 (2012)	Includes new HOBIT b-tagger
CDF METbb:	Phys. Rev. Lett. **109**, 111805 (2012)	Uses old SECVTX+JetProb b-taggers

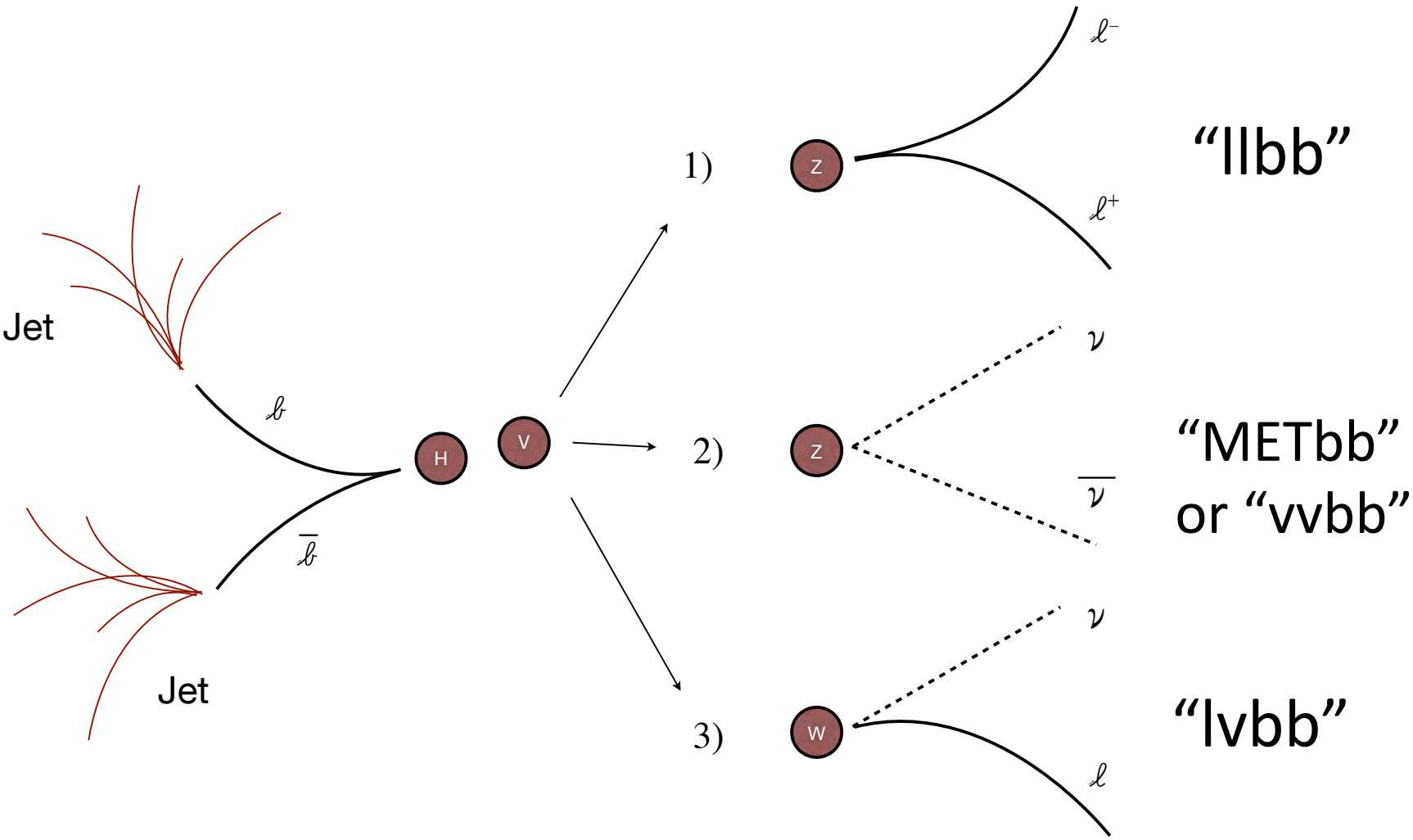
CDF Combined H→bb: Phys. Rev. Lett. **109**, 111802 (2012)

D0 lvbb:	Phys. Rev. Lett. **109**, 121804 (2012)
D0 llbb:	Phys. Rev. Lett. **109**, 121803 (2012)
D0 METbb:	Phys. Lett. B **716**, 285 (2012)

D0 Combined H→bb: Phys. Rev. Lett. **109**, 121802 (2012)

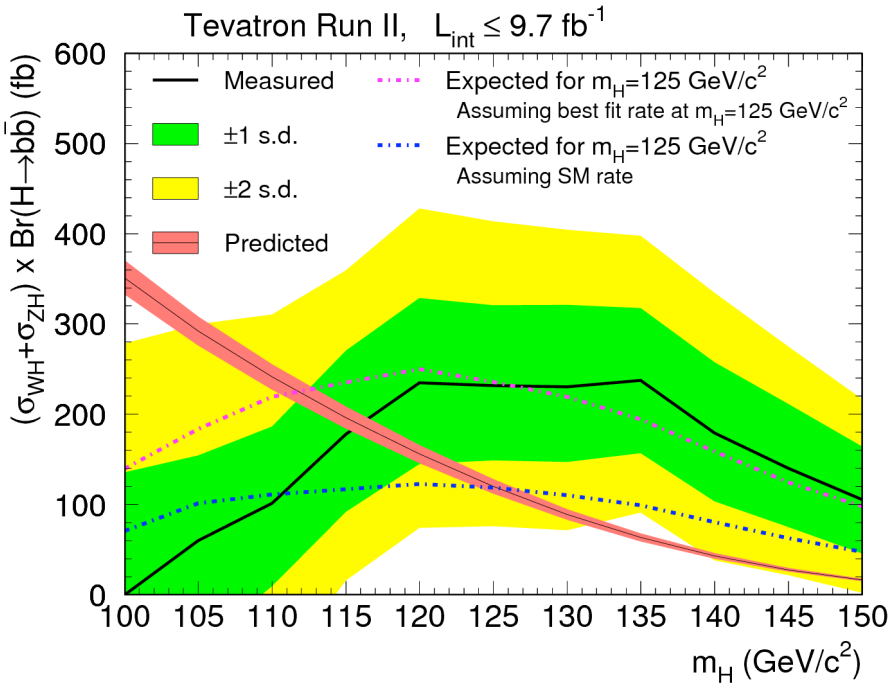
Tevatron Combined H→bb: Phys. Rev. Lett. **109**, 071804 (2012)

The Main Associated Production Search Channels

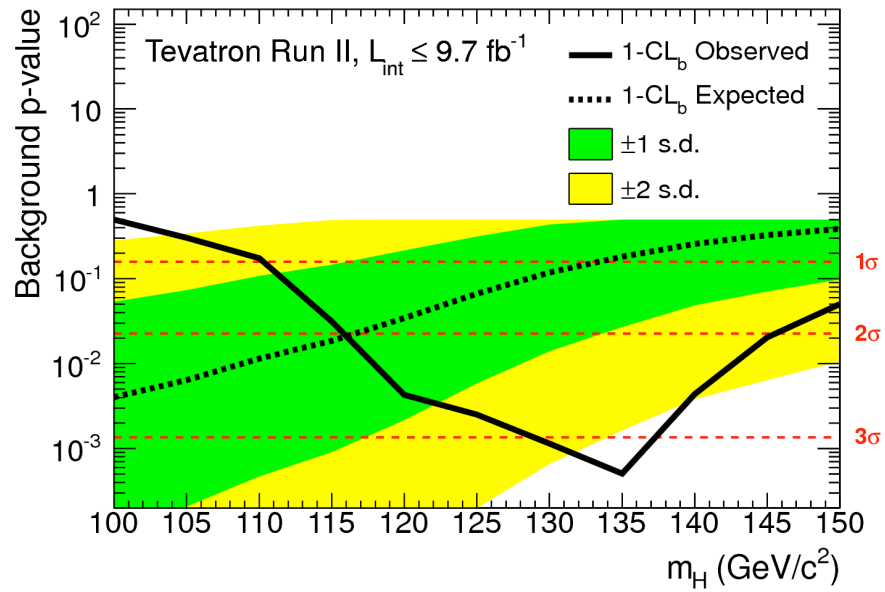


Drawing Credit: CMS Higgs TWiki.
CDF also seeks qqH→qqbb and ttH→ttbb

Tevatron H→bb Results, Summer 2012



Phys. Rev. Lett. **109**, 071804 (2012)



Cross section fit at m_H=125 GeV/c^2

$$(\sigma_{WH}+\sigma_{ZH}) \times B(H \rightarrow b\bar{b}) = 0.23^{+0.090}_{-0.080} \text{ (stat+syst) pb}$$

SM Prediction: 0.12 ± 0.01 pb

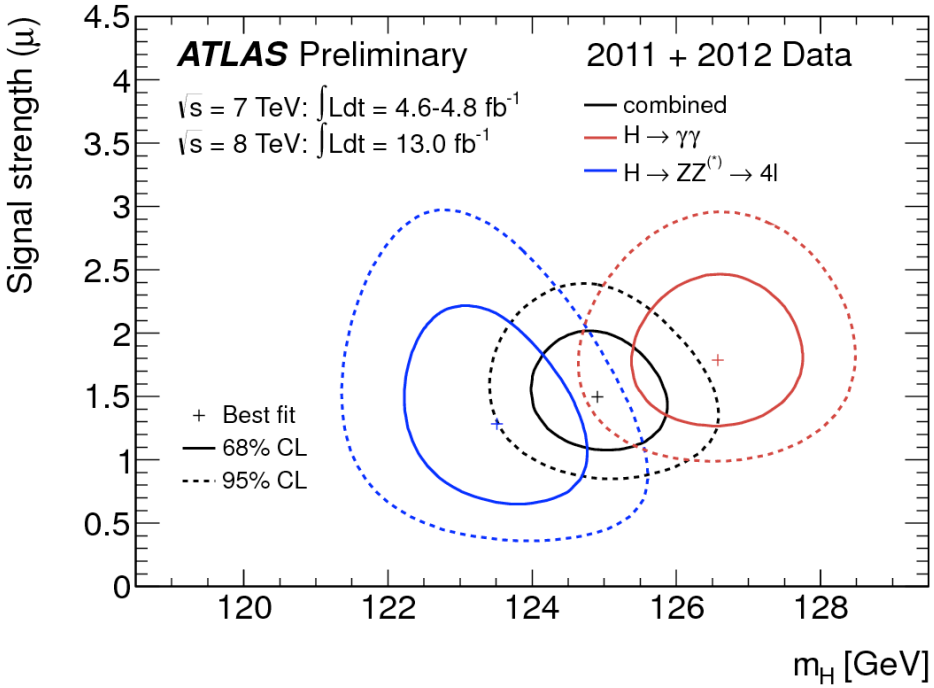
Maximum local significance: 3.3σ at m_H=135 GeV/c^2

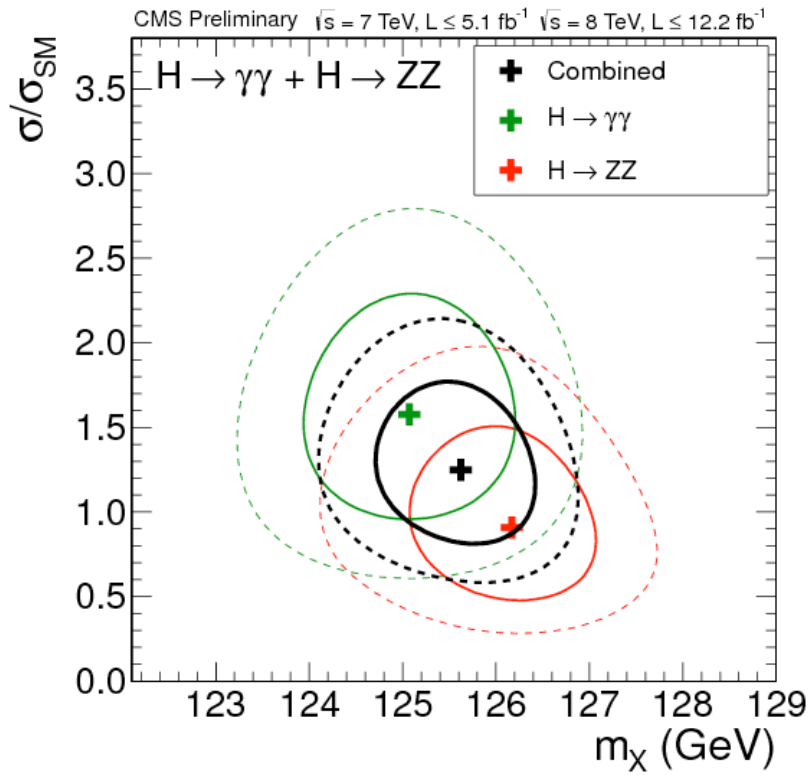
Global significance: 3.1σ – Evidence for VH→Vbb.
Local significance at m_H=125 GeV/c^2 is 2.8σ

Status from the LHC

(as of HCP 2012)

A Higgs-like particle is firmly established, its mass looks to be between 125 and 126 GeV, and its properties are consistent with the SM Higgs boson





Many more superb results are available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Recent Publications Contributing to the Final Higgs Combination

CDF:

METbb: Phys. Rev. D **87**, 052008 (2013).
HWW→lvlv: PRD in preparation. FERMILAB-PUB-13-029-E
All Hadronic final state: JHEP **1302**, 004 (2013)
ttH→ttbb: Phys. Rev. Lett **109**, 181802 (2012).
SM/SM4/FP/Coupling Combination: arXiv:1301.6668 (2013).
Submitted to Phys. Rev. D

D0:

H/WH/ZH→leptons+tau+jets: arXiv:1211.6993. Accepted by Phys. Rev. D
WH/ZH Trileptons and same-sign dileptons: arXiv:1302.5723 Submitted to Phys. Rev. D
H/WH/ZH→lvbb+lvjj + lvjjjj: arXiv:1301.6122 Accepted by Phys. Rev. D
H→Diphotons: arXiv:1301.5358 Accepted by Phys. Rev. D
H→WW→lvlv: arXiv:1301.1243 Accepted by PRD
SM/SM4/FP Combination: arXiv:1303.0823 Submitted to Phys. Rev. D

Tevatron Combination Manuscript: arXiv:1303.6346 Submitted to Phys. Rev. D

All CDF SM Search Channels

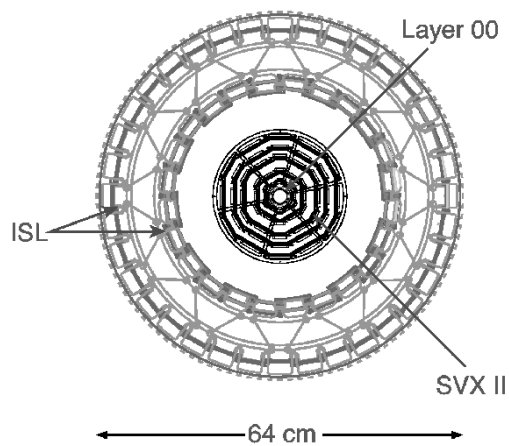
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)		9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^-b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	$H \to b\bar{b}$	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-$m_{\ell\ell}$)		9.7	110–200
$H \to W^+W^-$ (e-$\tau_{\rm had}$)+(μ-$\tau_{\rm had}$)		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	$H \to W^+W^-$	9.7	110–200
$WH \to WW^+W^-$ (tri-leptons with 1 $\tau_{\rm had}$)		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

All D0 SM Search Channels

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
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\rm had}\nu$		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
$VH \to \tau_{\rm had}\tau_{\rm had}\mu + X$	$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{\rm had}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

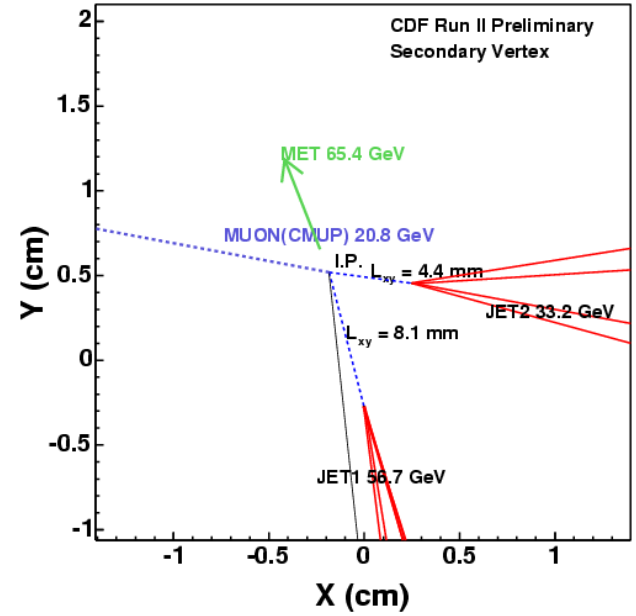
B-Tagging

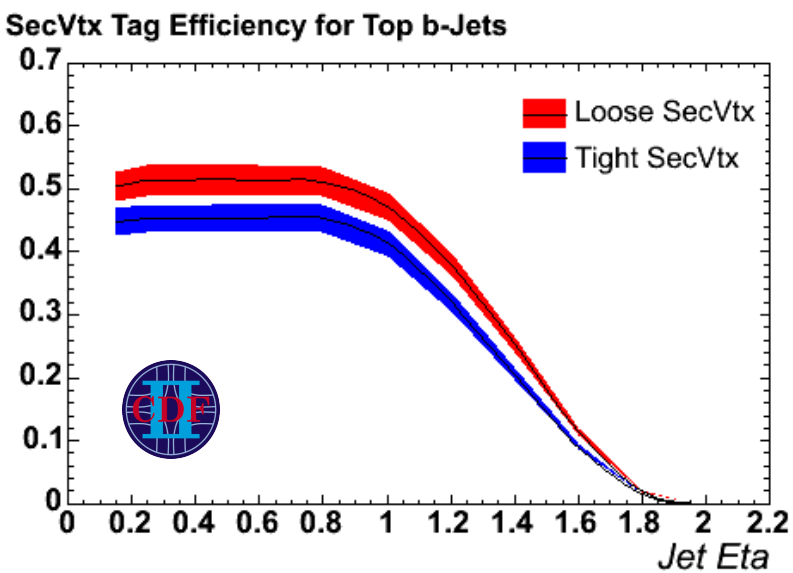
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm

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





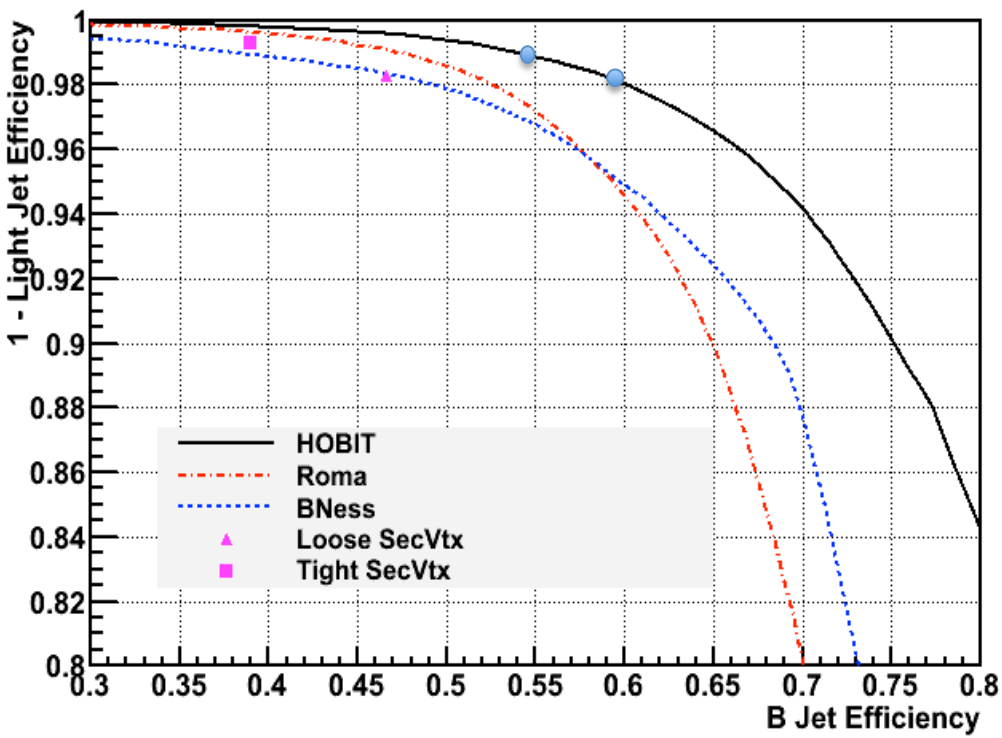
Mistag rates typically ~1% for light-flavor jets

Example candidate event (lvbb)

D0: Boosted Decision Tree tagging algorithm. Per-jet efficiency = 50-70% (of taggable jets) for 1-5% Mistag rate

CDF's HOBIT b-tagger – Improved Sensitivity With Respect to the SECVTX, Roma, and BNess taggers

A neural-network b-tagger using inputs from other b-taggers, as well as lepton ID to include semileptonically decaying B hadrons.



HOBIT Tight and Loose operating points chosen to have similar mistag rates as older SECVTX operating points.

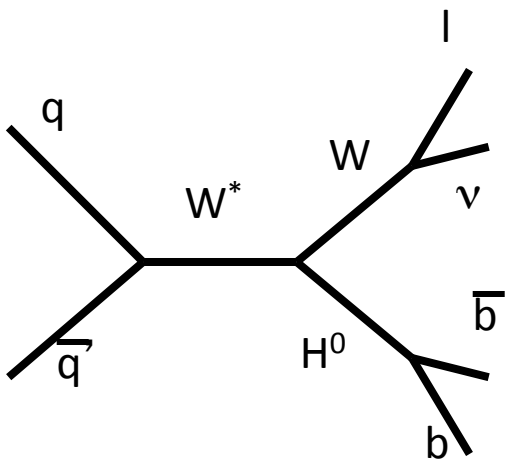
More signal
More *b* background
Similar LF background

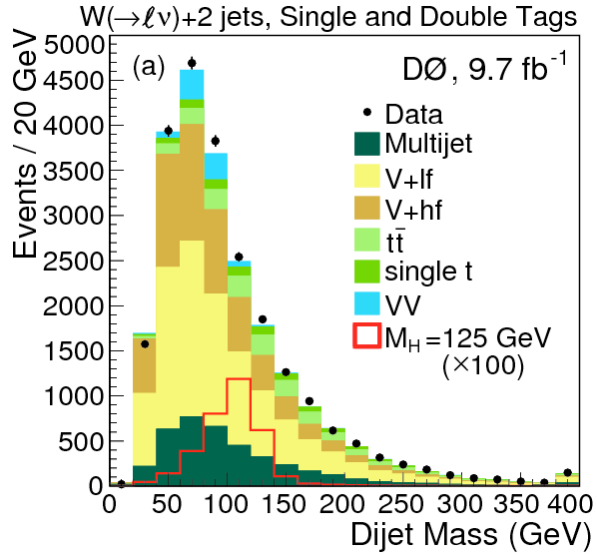
Operating Point	Mistag rate	SECVTX efficiency	HOBIT efficiency
Tight	1.4%	39%	54%
Loose	2.9%	47%	59%

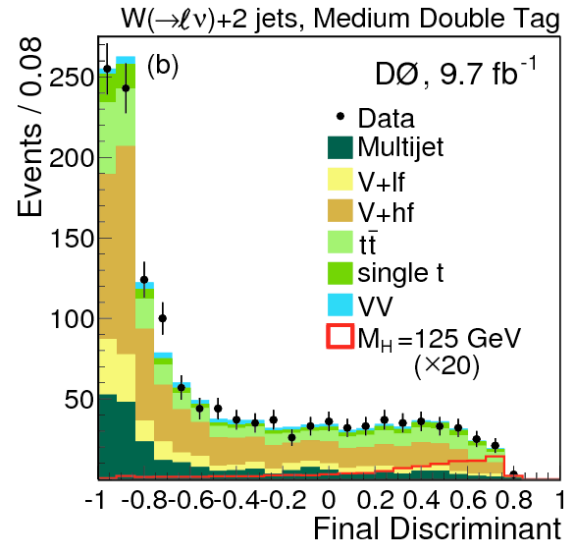
per-jet efficiencies shown

J. Freeman et al., Nucl. Instrum. Methods A **697**, 64 (2012).
see also M. Stancari, Fermilab Joint Experimental/Theoretical Seminar, Mar. 7 2012

Associated Production of a Higgs Boson with a W Boson

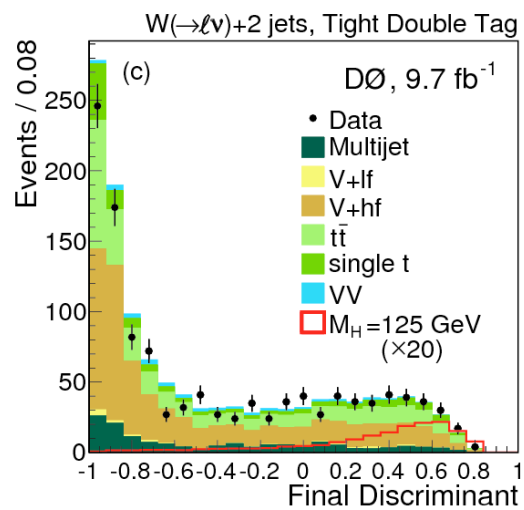






Double Tight Tag yields (D0)

Expected signal:	17.3±1.7 events of WH (m_H=125 GeV)
	1.9±0.1 events of ZH (m_H=125 GeV)
Expected Background:	10404±1059 events
Data	10071 events
Expected limit @125:	4.7*SM (2.8*SM for CDF)

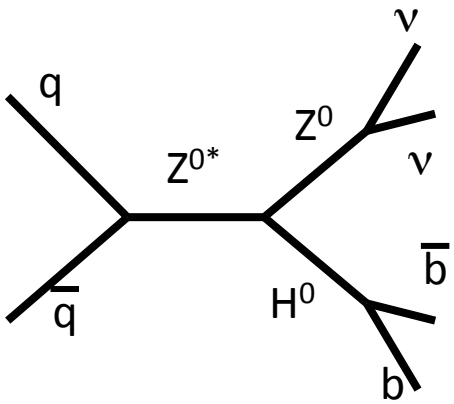


Dijet mass resolution: 13% to 23% depending on the number of jets and tags.

3-jet events or 1-tag events: more likely to misassign an ISR/FSR jet to the Higgs decay

D0 Collab., PRL **109**, 121804 (2012);
D0 Collab., arXiv:1301.6122 [hep-ex];
CDF Collab., PRL **109**, 111804 (2012)

ZH→llbb: A Fully Reconstructed Channel

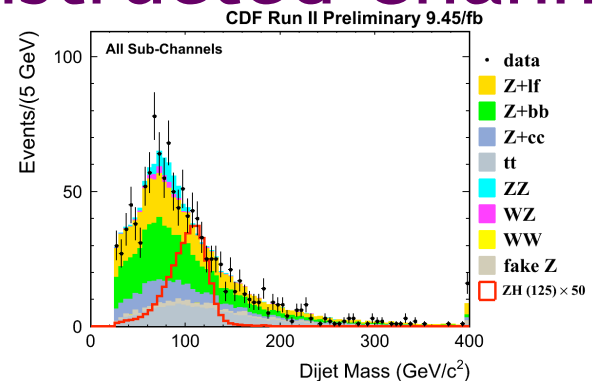


Excellent reconstruction countered by low Z→ll branching ratio

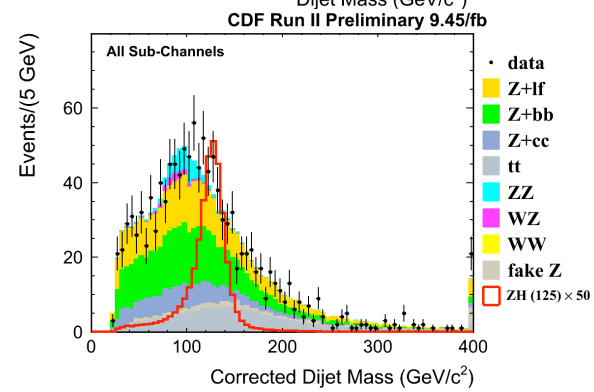
Double Tight Tag yields (CDF)
Signal (ZH) 1.9±0.3 events (m_H=125 GeV)
Background: 131±26 events
Data: 117 Events
Expected limit @125: 3.9*SM CDF, (5.1*SM for D0)

Very innovative channel!

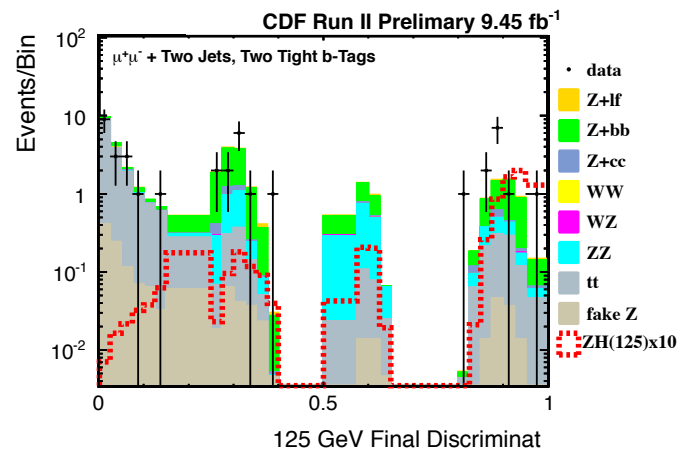
- Loose lepton ID. Tag and probe lepton ID efficiency calibration in data
- Split into 2 jet, 3 jet, single, double, tight, and loose b-tags
- NN dijet mass using MET projections
- Cascade of neural networks: Train networks to separate ttbar, Diboson, Wbb backgrounds from signal.



"Raw" dijet mass

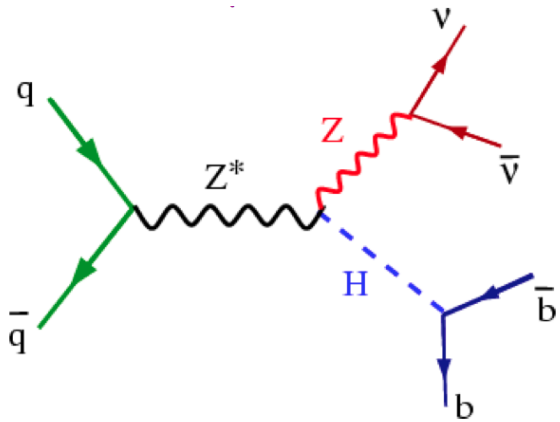


Dijet mass after NN Correction 12% resol. in some channels

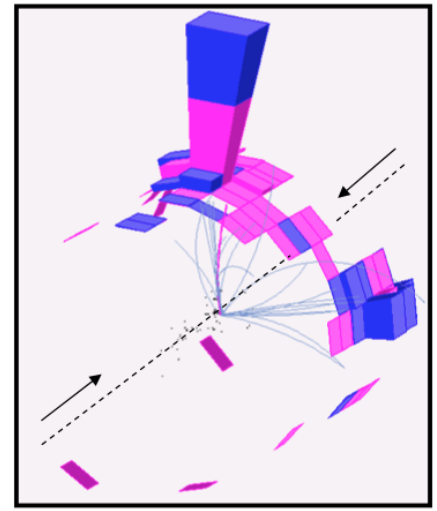


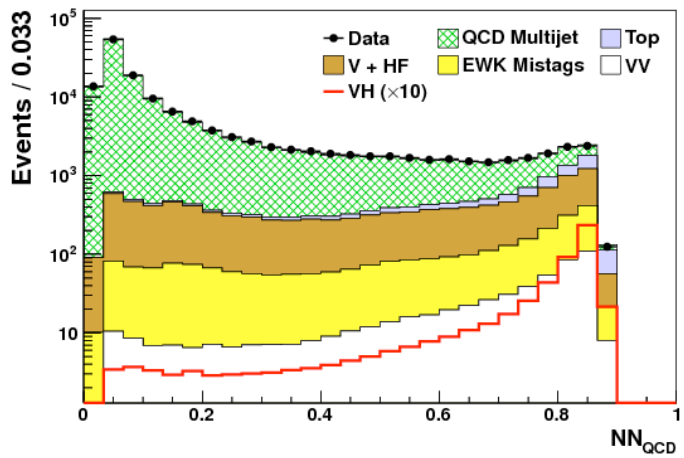
CDF Collab., PRL **109**, 11803 (2012)
D0 Collab., PRL **109**, 121803 (2012)

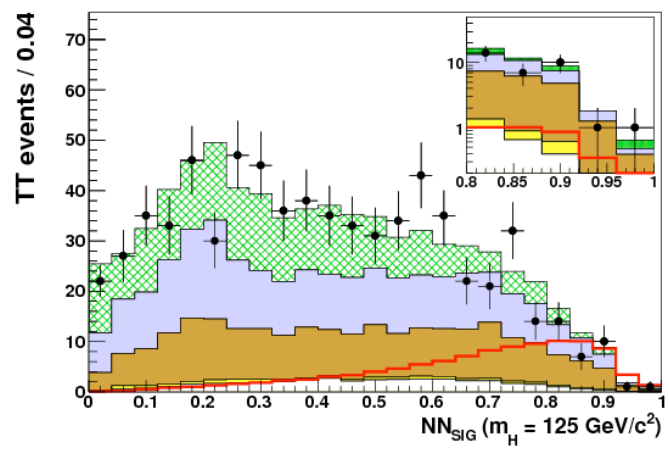
VH→METbb Analysis

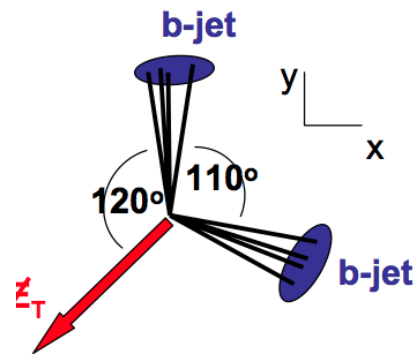


Double-tight tags, CDF yields:
Signal (WH125): 5.3±0.5
Signal (ZH125): 5.4±0.5
Background: 759±86
Data: 692
Expected limit: 3.3*SM (3.9*SM for D0)





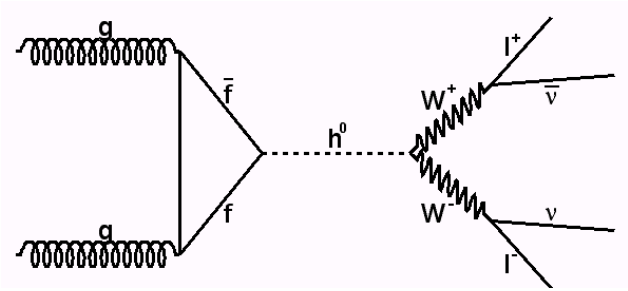




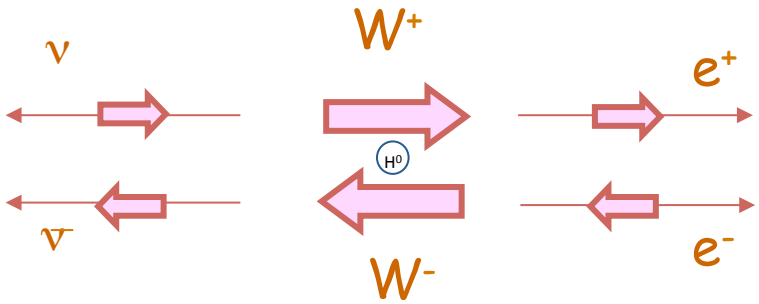
Cascade of neural networks:
First anti-QCD, second Higgs vs. remaining backgrounds

CDF Collab., PRL **109**, 111805 (2012)
Updated with HOBIT: PRD **87**, 052008 (2013)
D0 Collab., Phys. Lett. B **716**, 285 (2012)

H→WW Searches

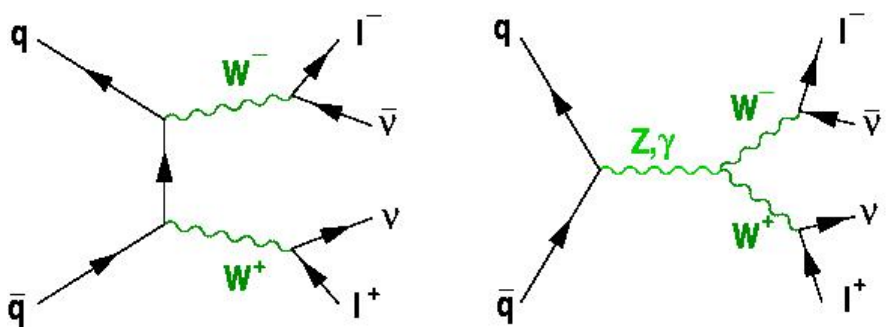


Largest signal is from gluon fusion, but WH, ZH, and VBF contribute as well.



ΔR_{ll} tends to be smaller in signal events than for background events

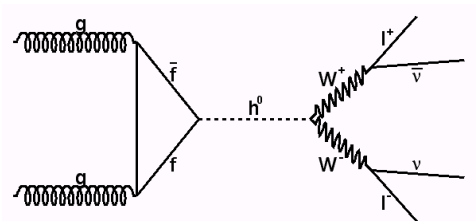
Dominant background at the Tevatron is nonresonant WW production

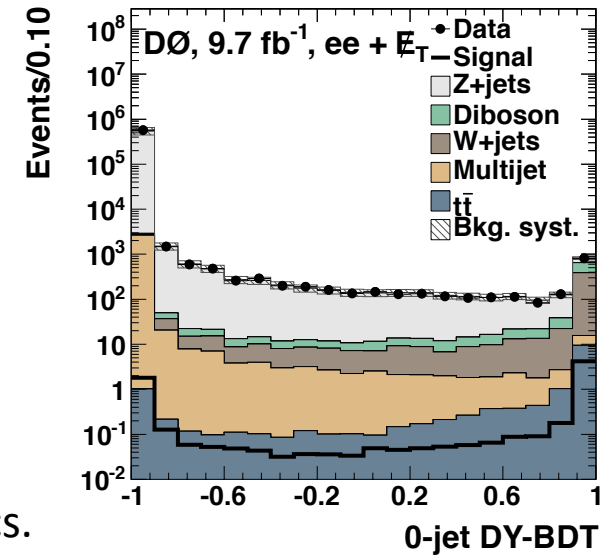


But we split the samples into
lνlν + 0j
lνlν + 1j
lνlν + 2 or more jets
and the backgrounds vary by subsample.

D0 Collab., PRD **86**, 032010 (2012)
CDF Collab., FERMILAB-PUB-13-029-E (in preparation)

H→WW Searches





Signature: Two oppositely-signed leptons, large missing E_T. Low $\Delta\Phi_{ll}$, low ΔR_{ll}

Large DY background in ee and μμ channels, not so much in eμ. DY has low missing E_T, m_{ll} near m_Z, and other characteristics.

DY BDT removes most of DY(+jets)

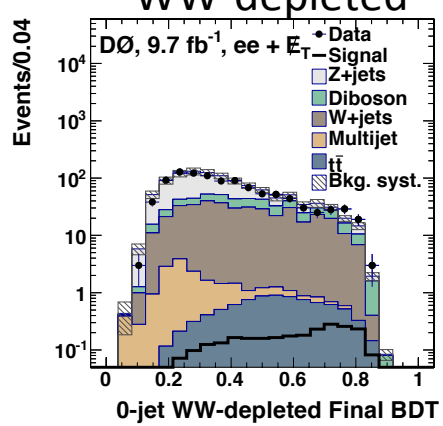
D0 Collab., arXiv:1301.1243 [hep-ex]

Recent improvements:

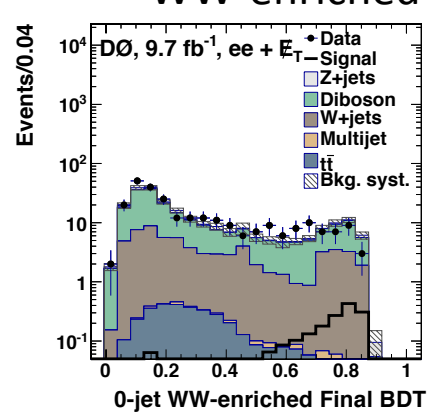
- Looser lepton ID
- low-m_{ll} channel,
- modify isolation requirement so leptons don't spoil each other's isolation.
- Split channels into more categories:

Data calibration of lepton ID efficiency for new loose lepton categories.
Control regions to validate backgrounds: DY, WW, Wγ, W+jets, ttbar

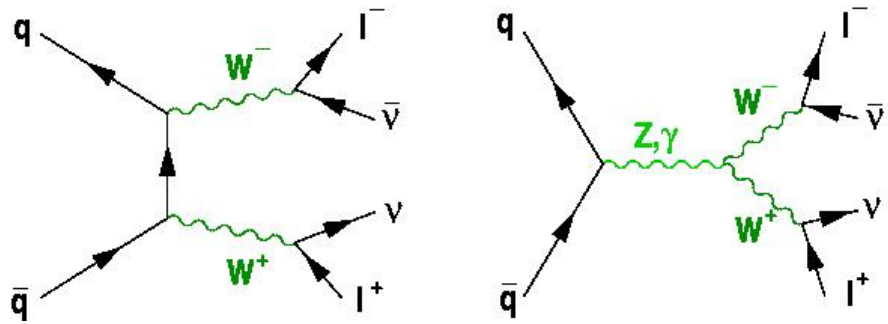
WW-depleted



WW-enriched

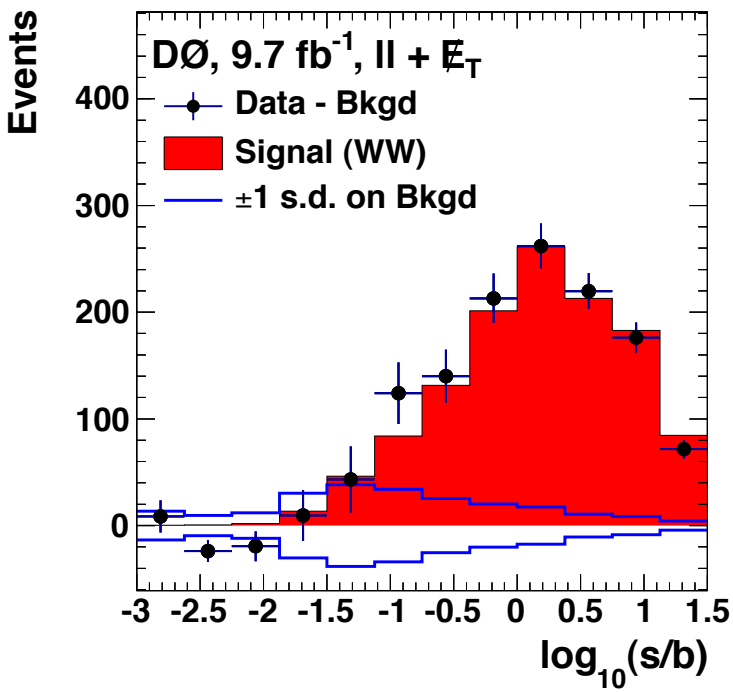


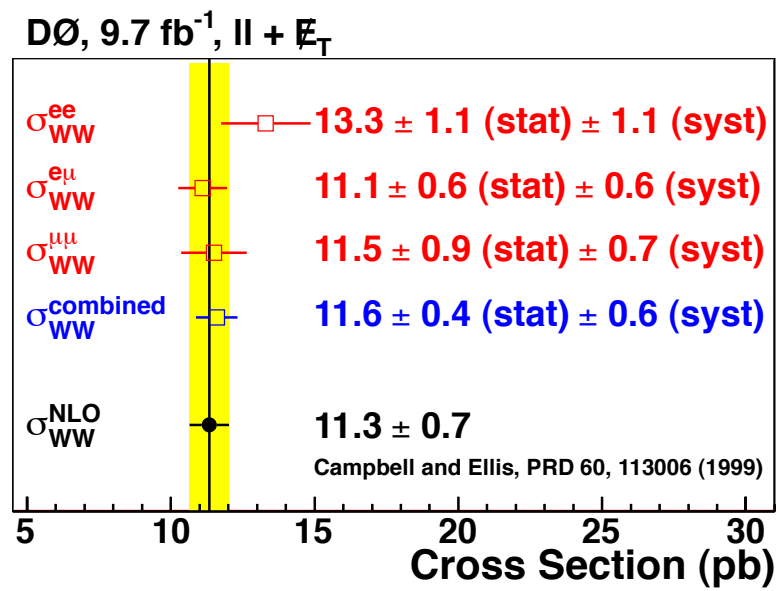
Validation of H→WW Analysis by Measuring the WW Cross Section



Same Selection, Similar MVA's

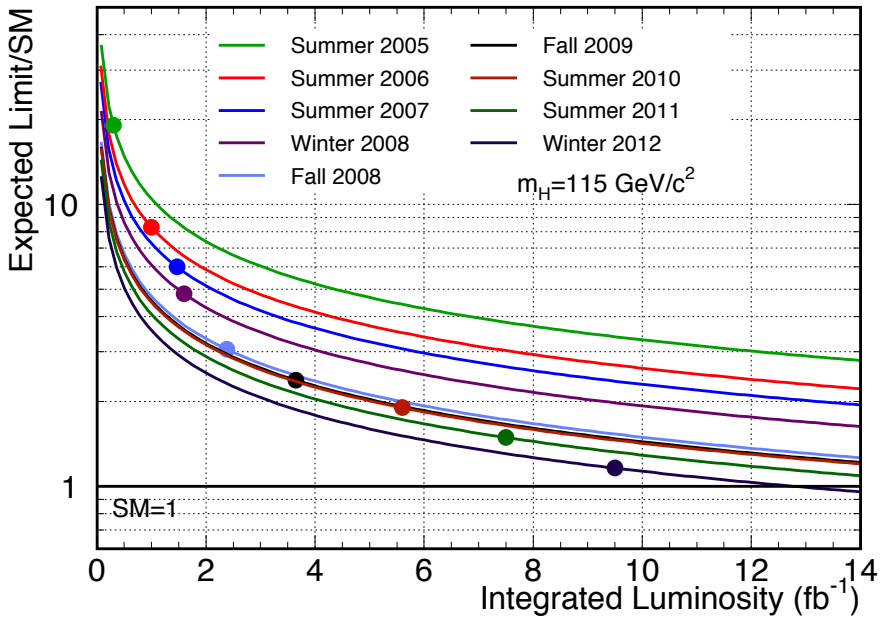
Measure WW cross section of (1.02±0.06)*$SM_{(MCFM\ v6.0)}$



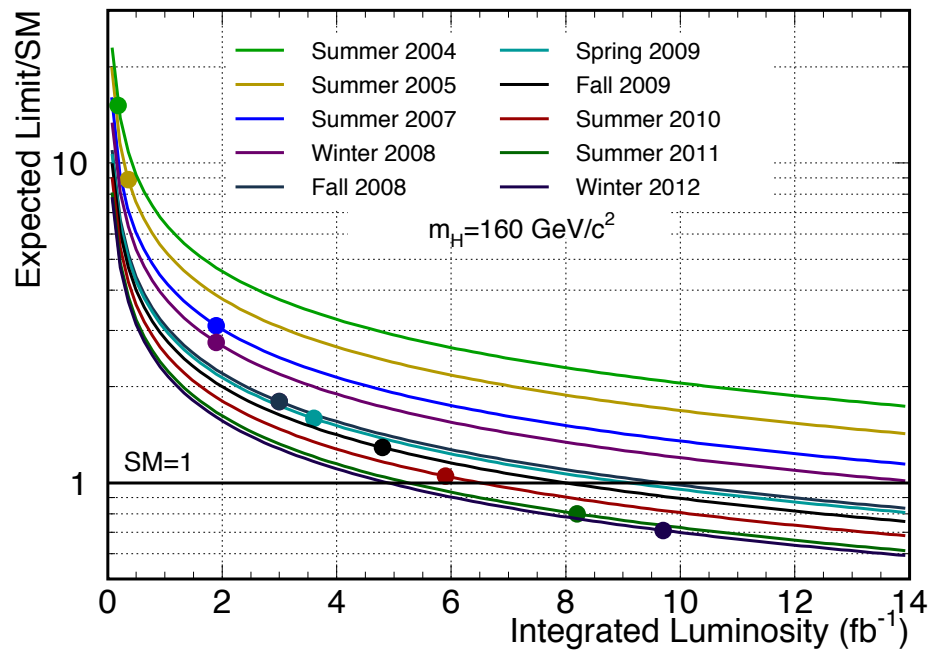


D0 Collab., arXiv:1301.1243 [hep-ex]

Sensitivity Evolution over Time



CDF sensitivities shown. D0's sensitivities are similar

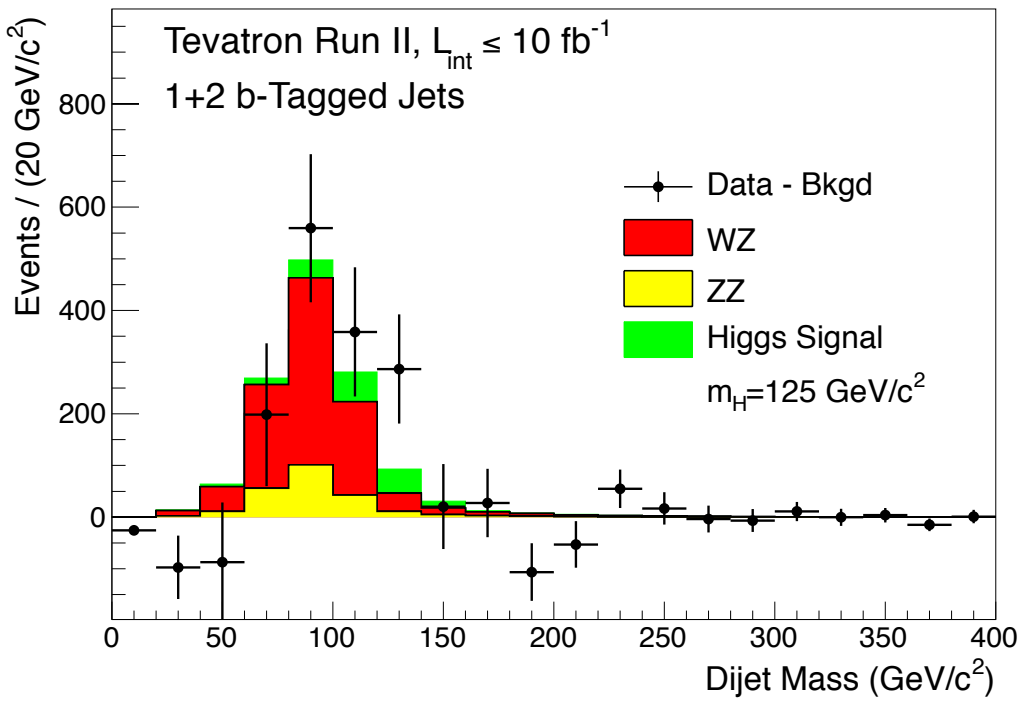


We collected data, and we also learned how to get more out of the data.

- Better MVA's
- Better Event Selection
- Better lepton ID
- Better jet energy resolution
- More triggers
- More analysis categories
- Sharing improvements between analyses

Tevatron Diboson Search in the Higgs Analyses

Check of the VH→Vbb channels using the WZ+ZZ signal as a standard candle



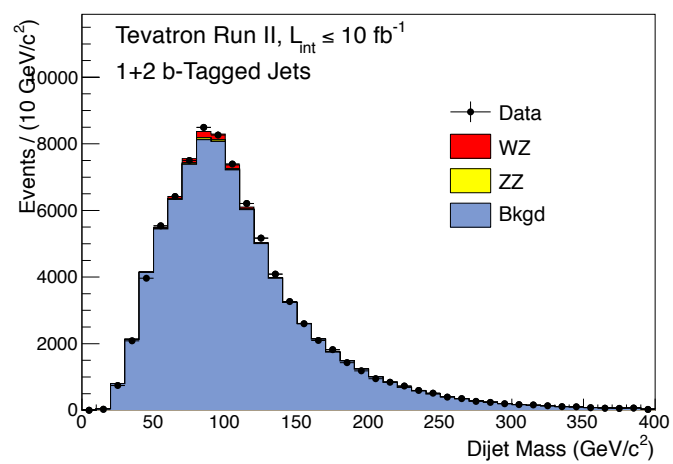
A look at the summed m_{jj} distribution

Measurement:

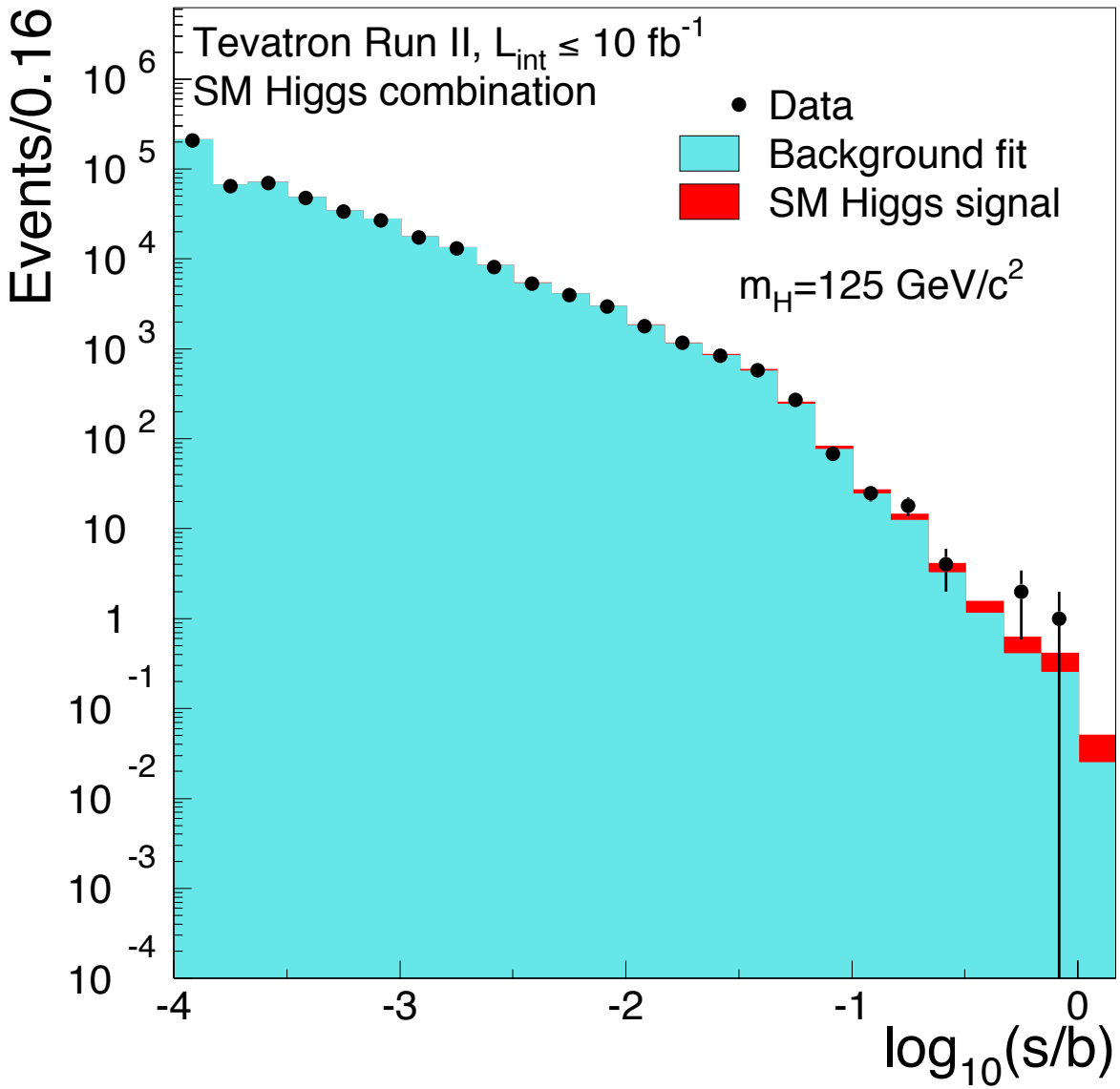
$$\sigma(WZ+ZZ) = 3.0 \pm 0.6 \text{ pb}$$

SM Prediction:

$$\sigma(WZ+ZZ) = 4.4 \pm 0.3 \text{ pb}$$



SM Combined Data Summary at m_H=125 GeV/c^2

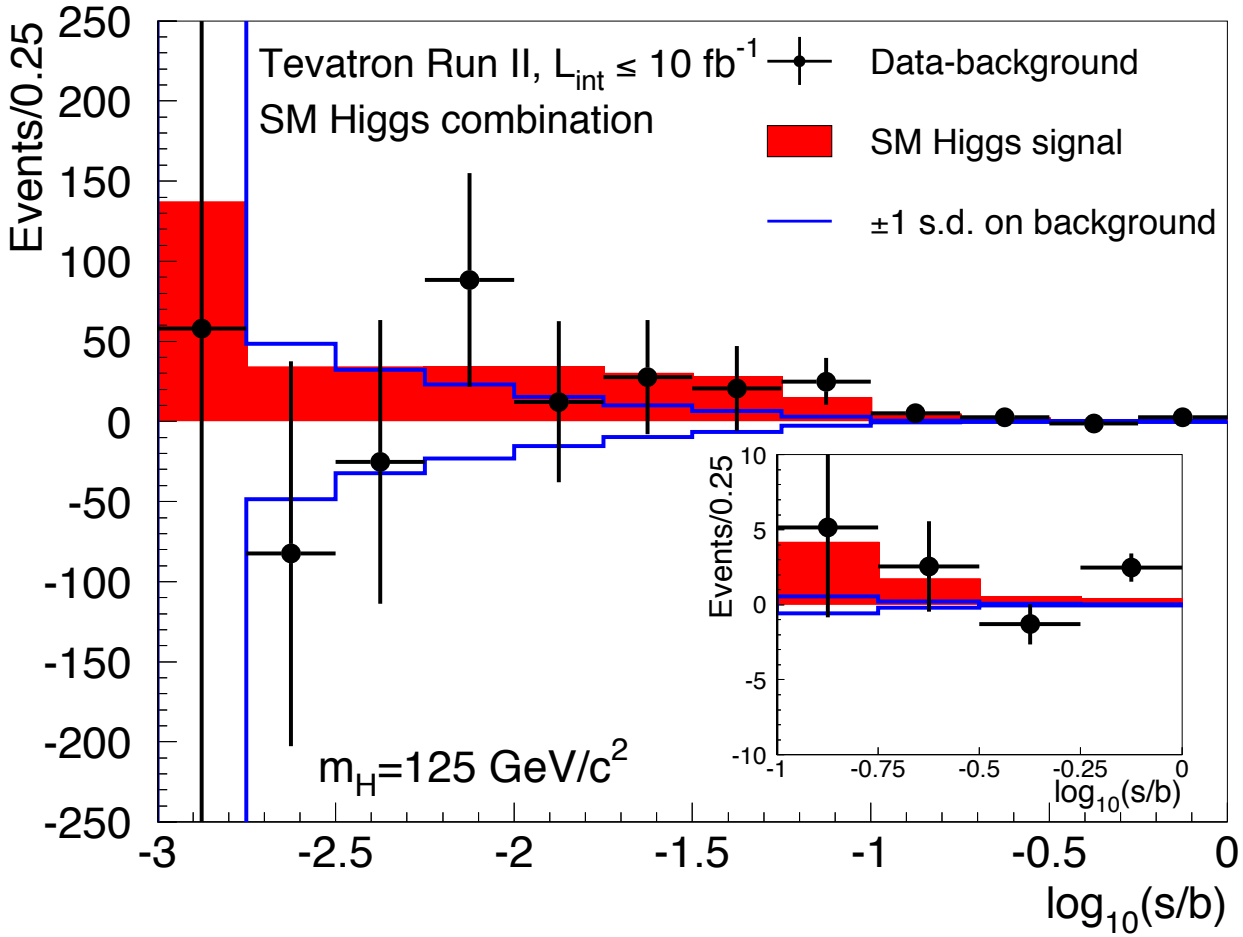


Background Hypothesis fit to data

Bins of similar s/b added together

Data error bars are sqrt(n_{obs})

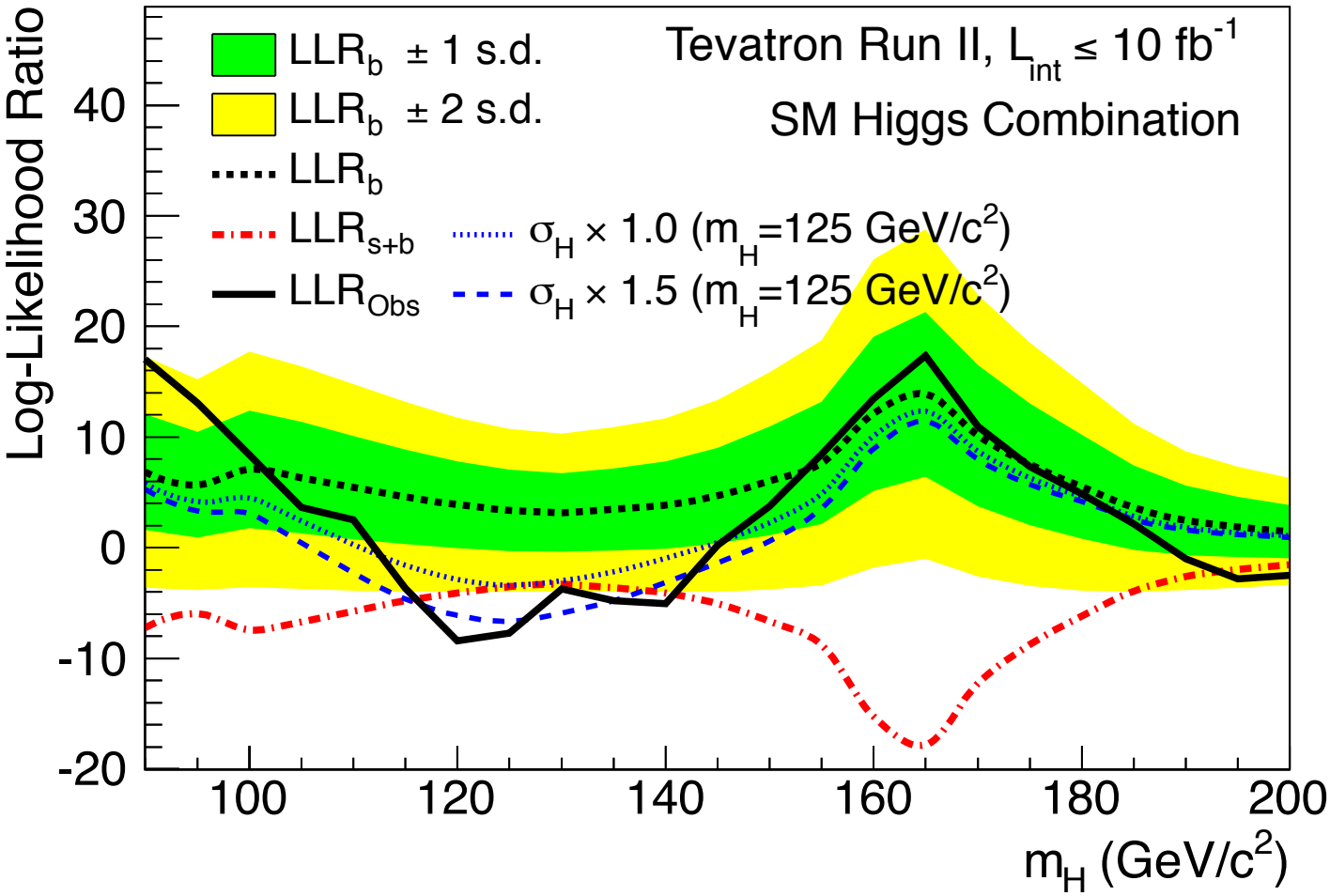
SM Combined Data Summary at m_H=125 GeV/c^2



Same as before, but fitted background subtracted from the data.

Data error bars are sqrt(s+b_{fit})

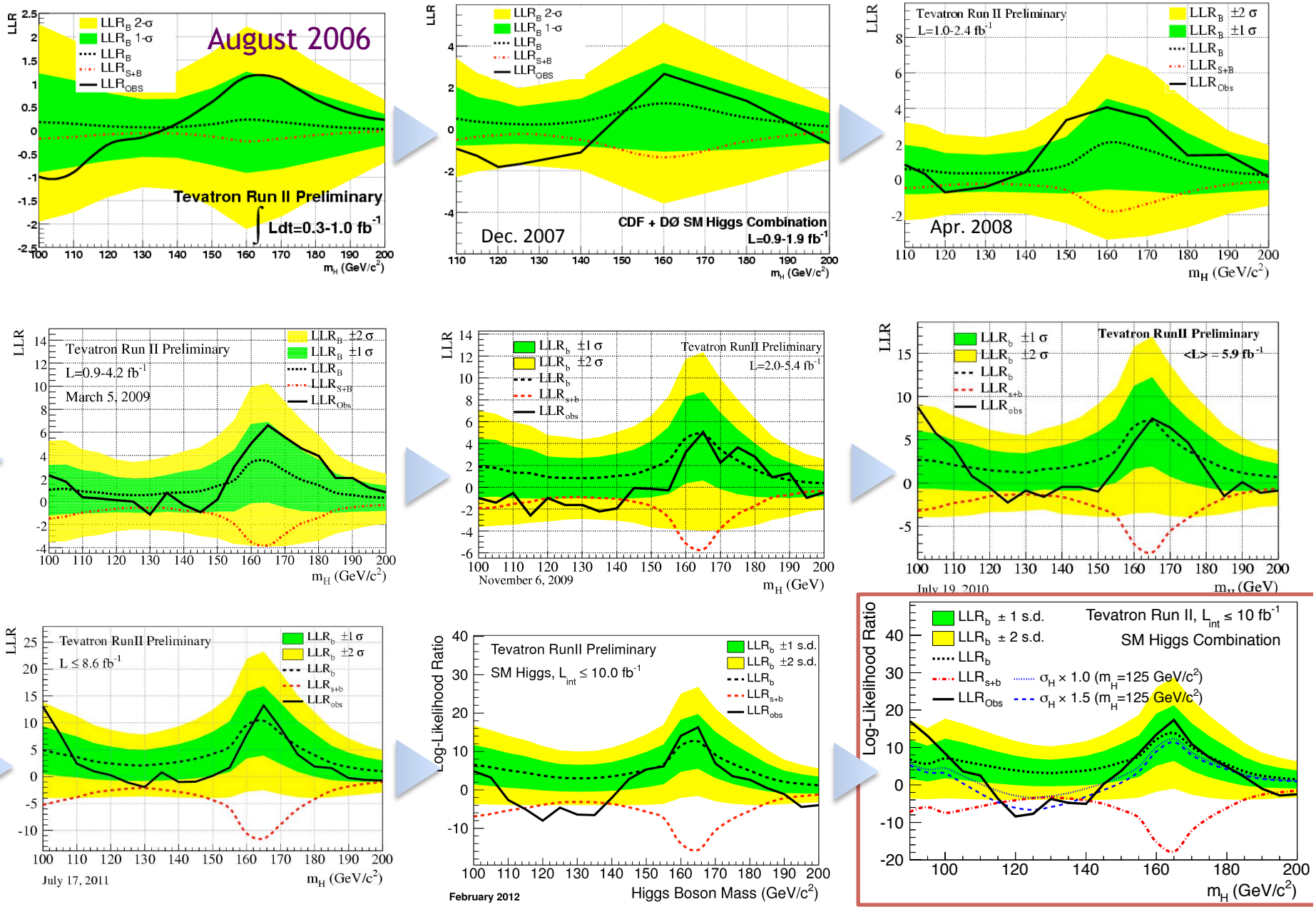
Tevatron Combined SM LLR Distributions



$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,H_1,\hat{\theta})}{L(\text{data}\,|\,H_0,\hat{\hat{\theta}})}\right)$$

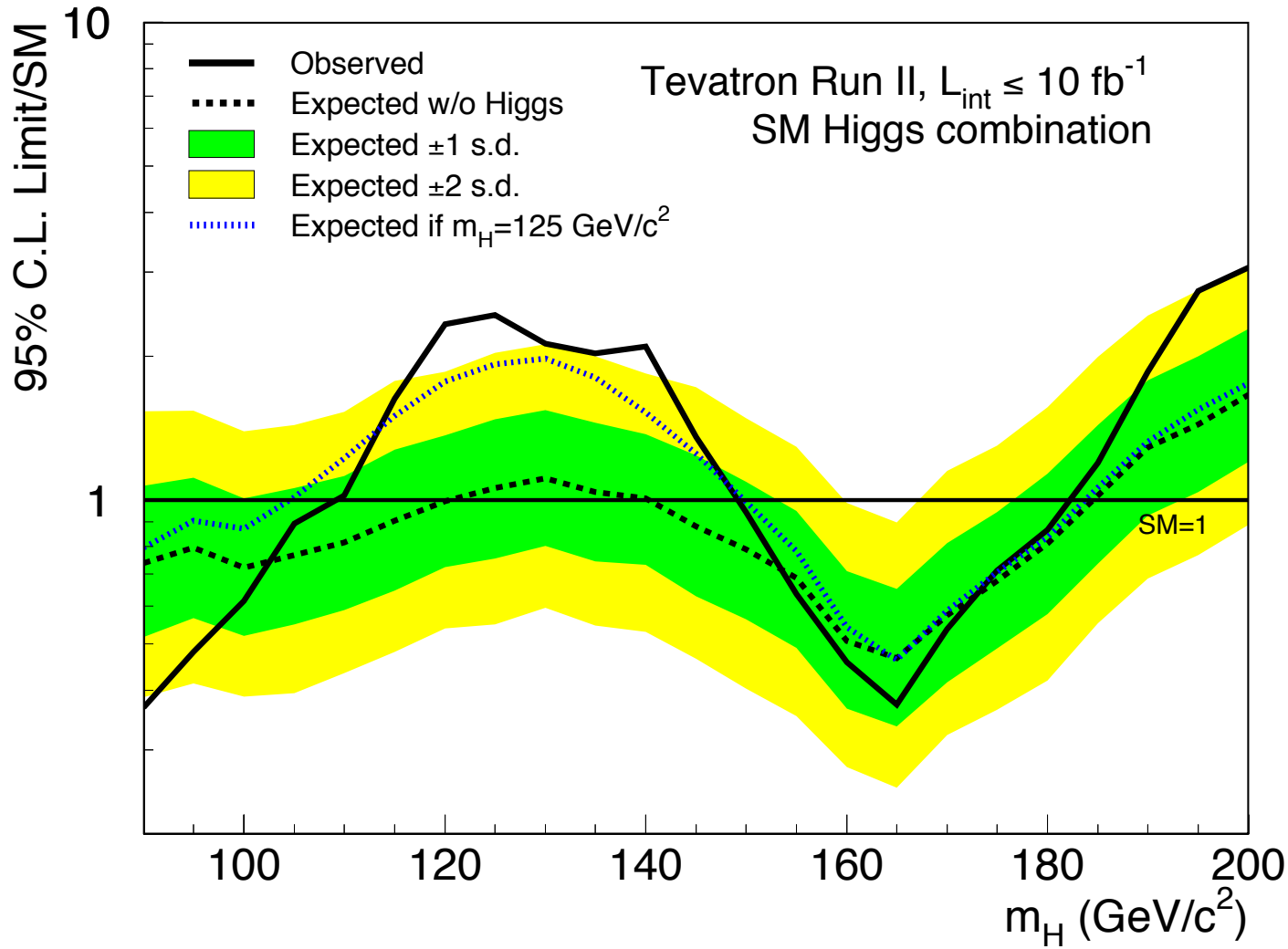
LLR is a ratio of the compatibility of the data with the signal+background hypothesis and the background-only hypothesis.
Data show a clear preference for a Higgs boson with m_H between 115 and 140 GeV

Tevatron Combined LLR Over the Years



March 2013: Final

Tevatron Final SM Higgs Rate and Mass Limits

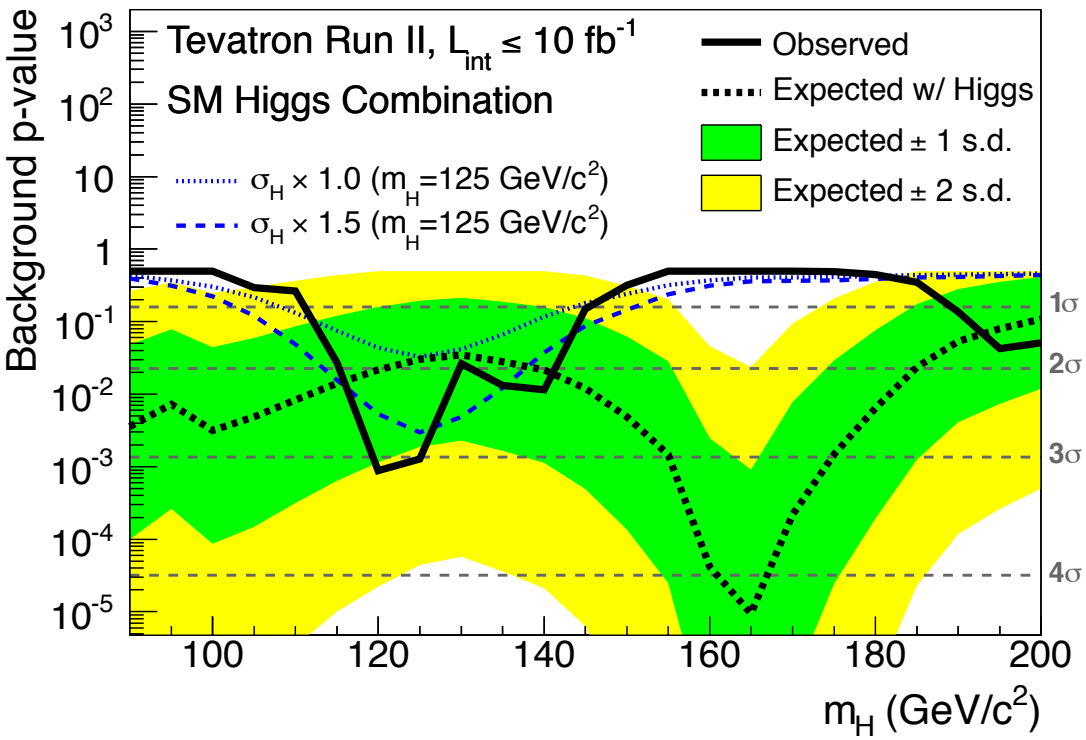


Excluded regions: $90 < m_H < 109$ GeV/c^2 and $149 < m_H < 182$ GeV/c^2

Expect to exclude if no Higgs: $90 < m_H < 120$ GeV/c^2 and

$140 < m_H < 184$ GeV/c^2

Tevatron Combined SM Higgs Boson Search p-value



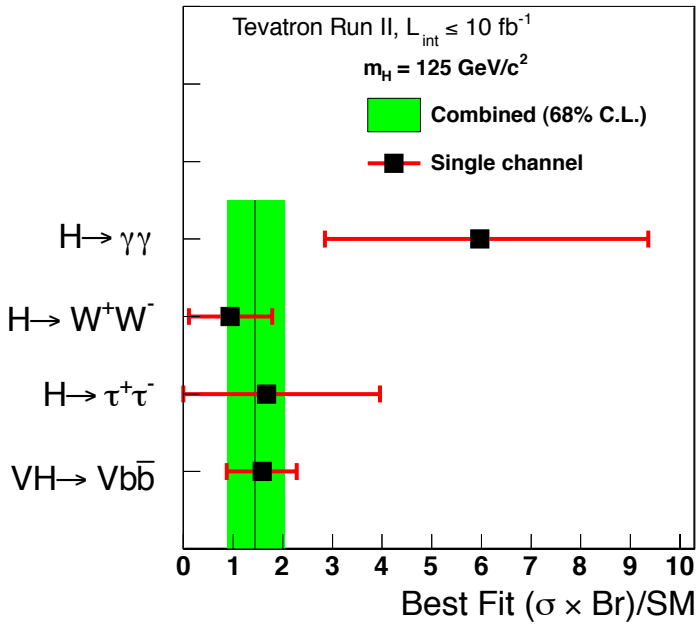
Observed local significance at m_H=125 GeV/c^2 is 3.1σ

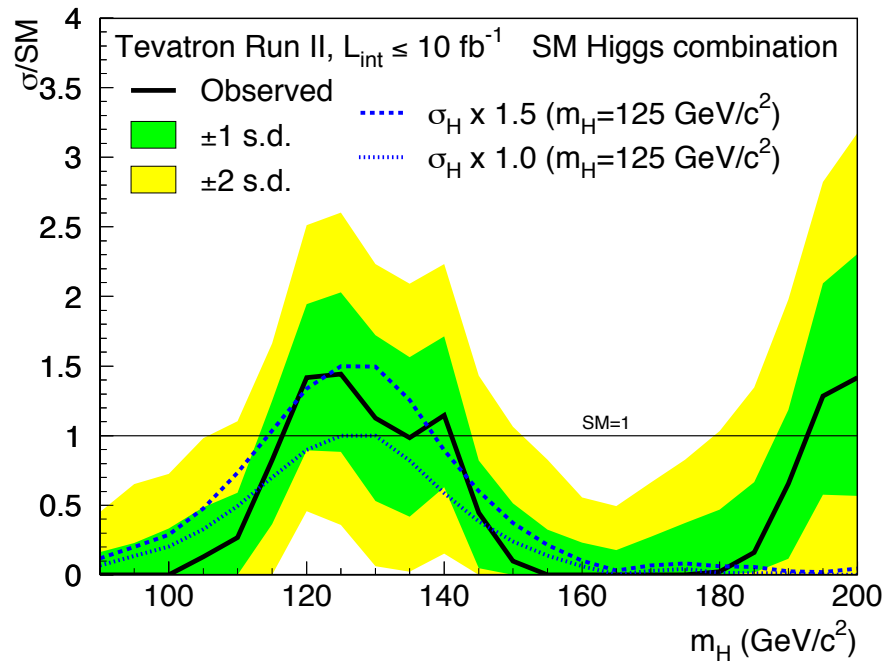
Expected significance assuming m_H=125 GeV/c^2 is shown with a dotted line (not quite 2σ)

Look-Elsewhere Effect:

- m_H~125 GeV has been firmly established by the LHC
- CDF+D0's mass resolution is not very sharp -- ~2 independent search results in H→bb, ~2 in H→WW
- Technical challenge – MVA's trained at each m_H separately. Histograms of predictions exchanged. Would need to exchange correlated pseudoexperiments to compute LEE exactly.

Best-Fit Tevatron Combined Cross Sections at m_H=125 GeV/c^2





$$VH \rightarrow Vb\bar{b}: \quad 1.59^{+0.69}_{-0.72} \times \mathrm{SM}$$

$$H \rightarrow \tau^+\tau^-: \quad 1.68^{+2.28}_{-1.68} \times \mathrm{SM}$$

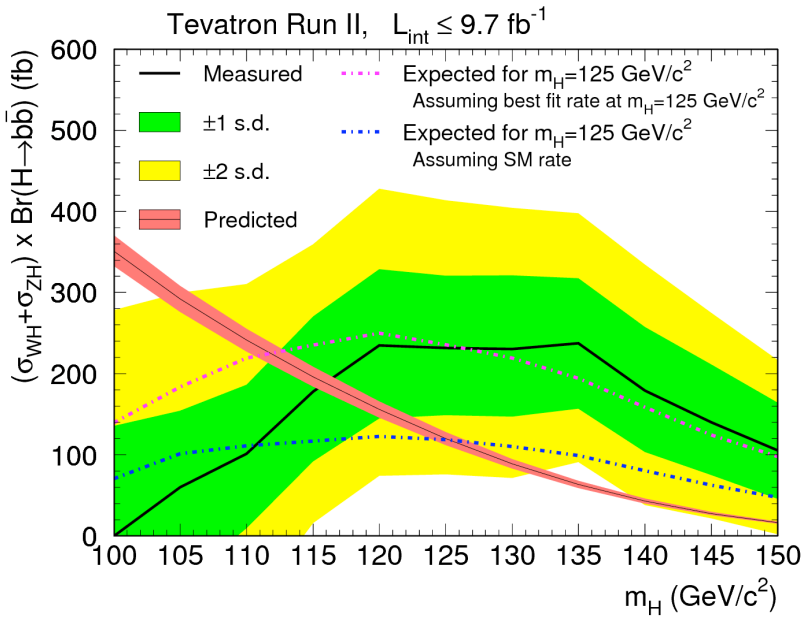
$$H \rightarrow W^+W^-: \quad 0.94^{+0.85}_{-0.83} \times \mathrm{SM}$$

$$H \rightarrow \gamma\gamma: \quad 5.97^{+3.39}_{-3.12} \times \mathrm{SM}$$

$$\mathrm{Combined}: \quad 1.44^{+0.59}_{-0.56} \times \mathrm{SM}$$

Final Tevatron Combined VH→Vbb Cross Section Measurements

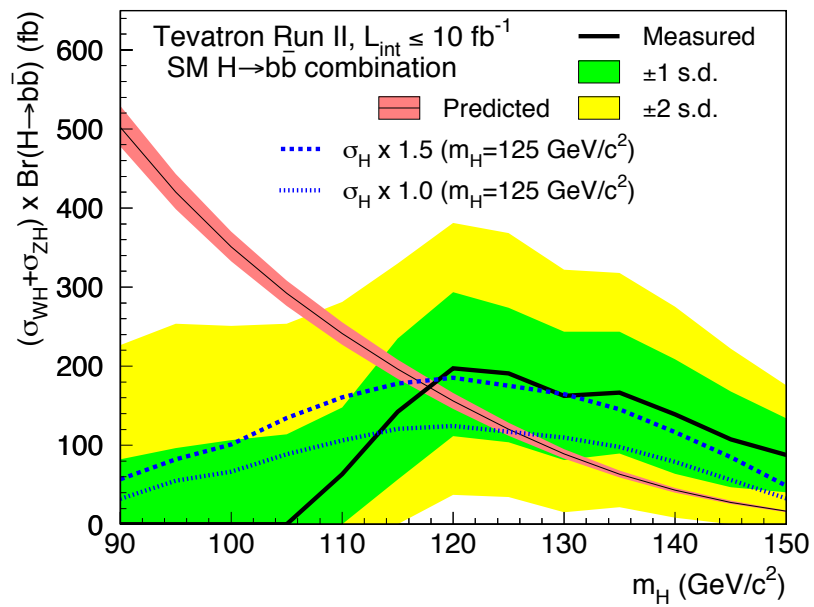
Phys. Rev. Lett. **109**, 071804 (2012)



at m_H=125 GeV/c^2

$$\sigma(WH+ZH)\times Br(H\to b\bar{b}) = 0.23^{+0.09}_{-0.08}\ \text{pb}$$

arXiv:1303.6346



At m_H=125 GeV/c^2, the measured rate is

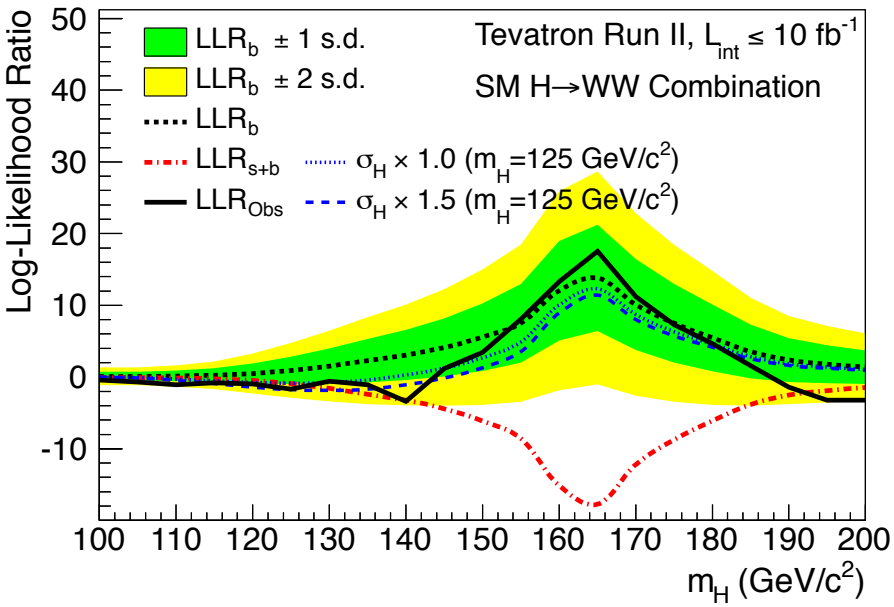
$$\sigma(WH+ZH)\times Br(H\to b\bar{b}) = 0.19^{+0.08}_{-0.09}\ \text{pb}$$

The change is due to CDF's updated METbb channel

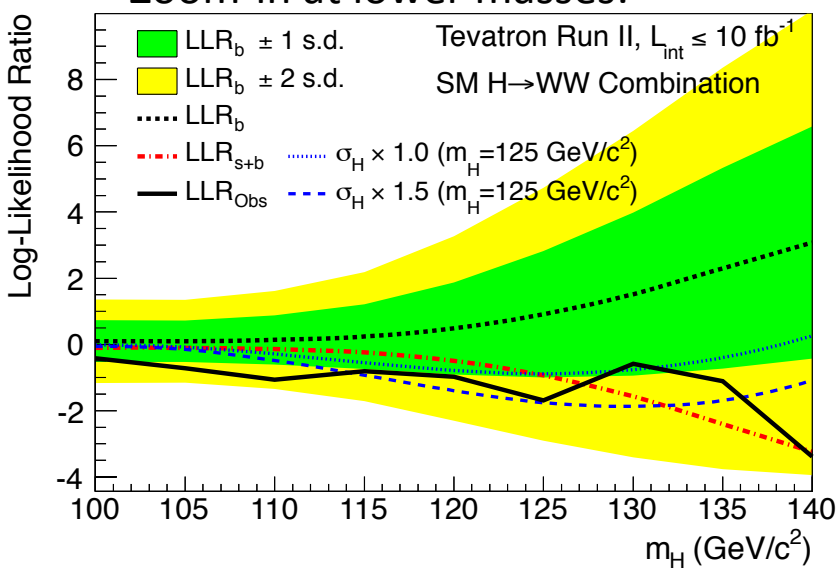
The SM prediction is

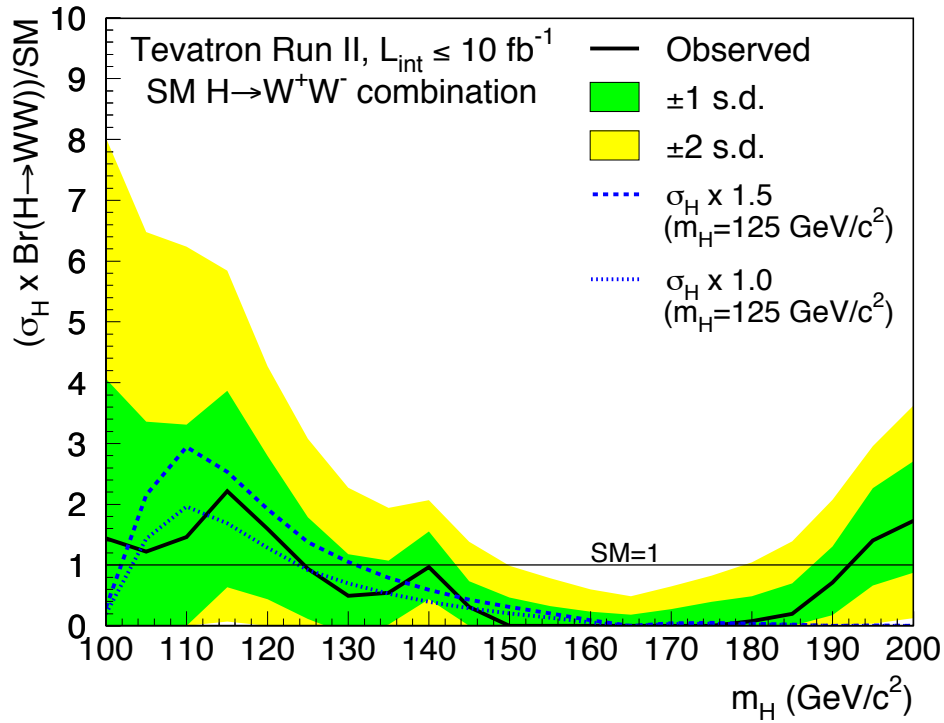
$$\sigma(WH+ZH)\times Br(H\to b\bar{b}) = 0.120 \pm 0.008\ \text{fb}$$

Tevatron Combined H→WW Searches

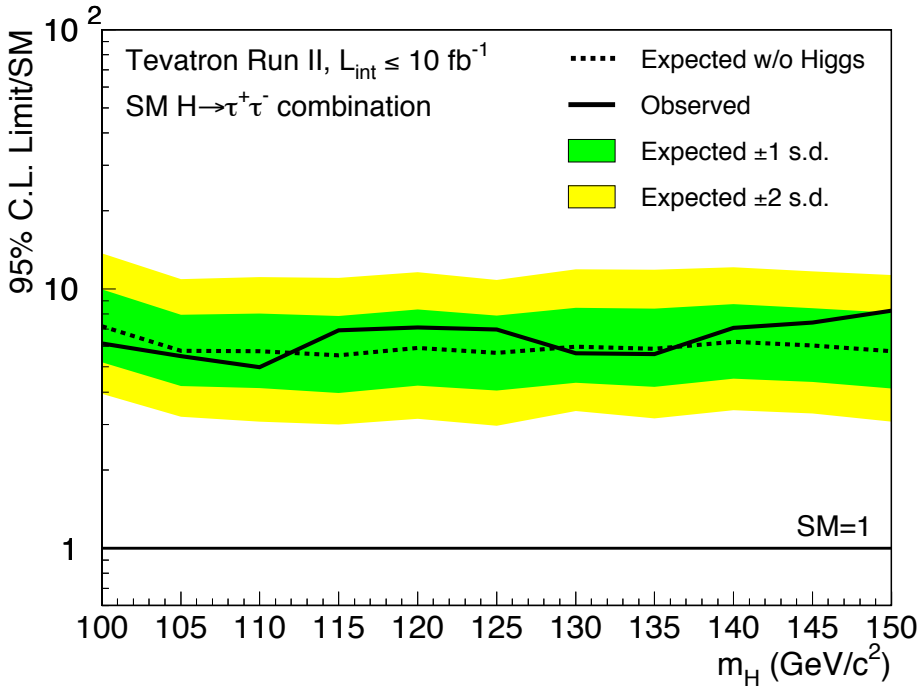


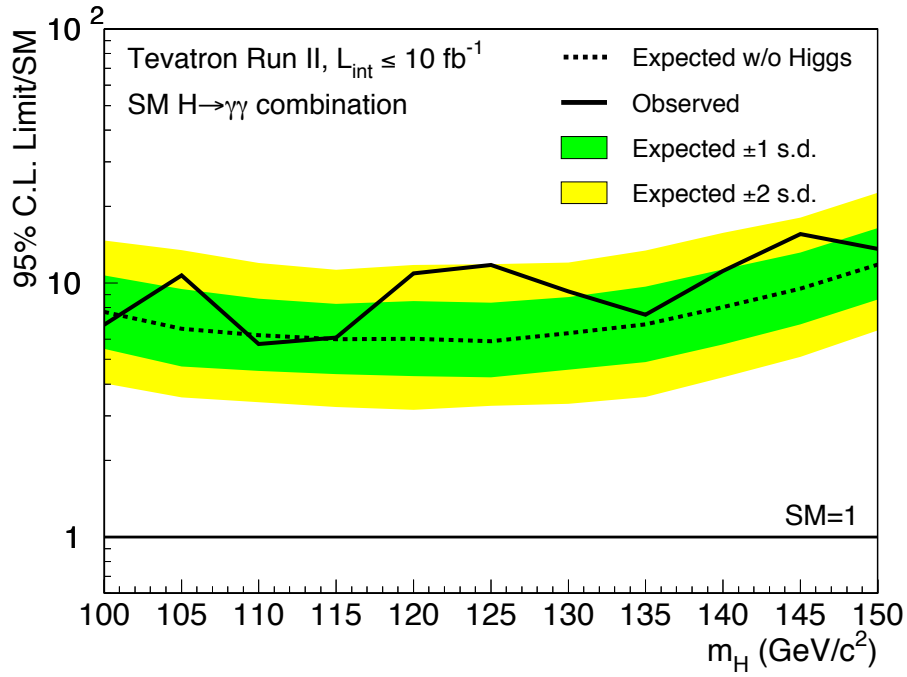
Zoom-in at lower masses:





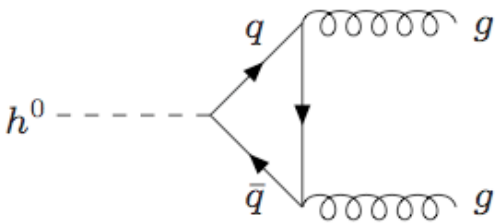
Tevatron Combined H→$\tau^+\tau^-$ and H→$\gamma\gamma$ Searches



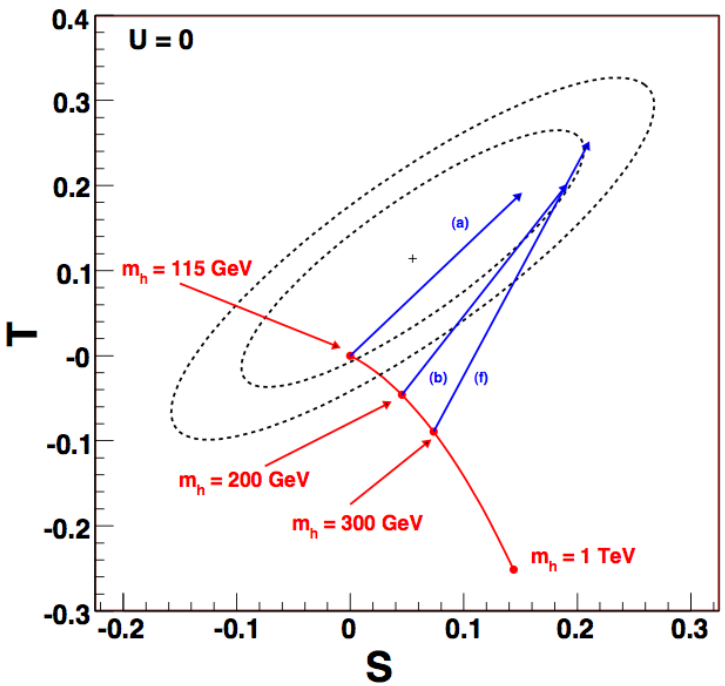


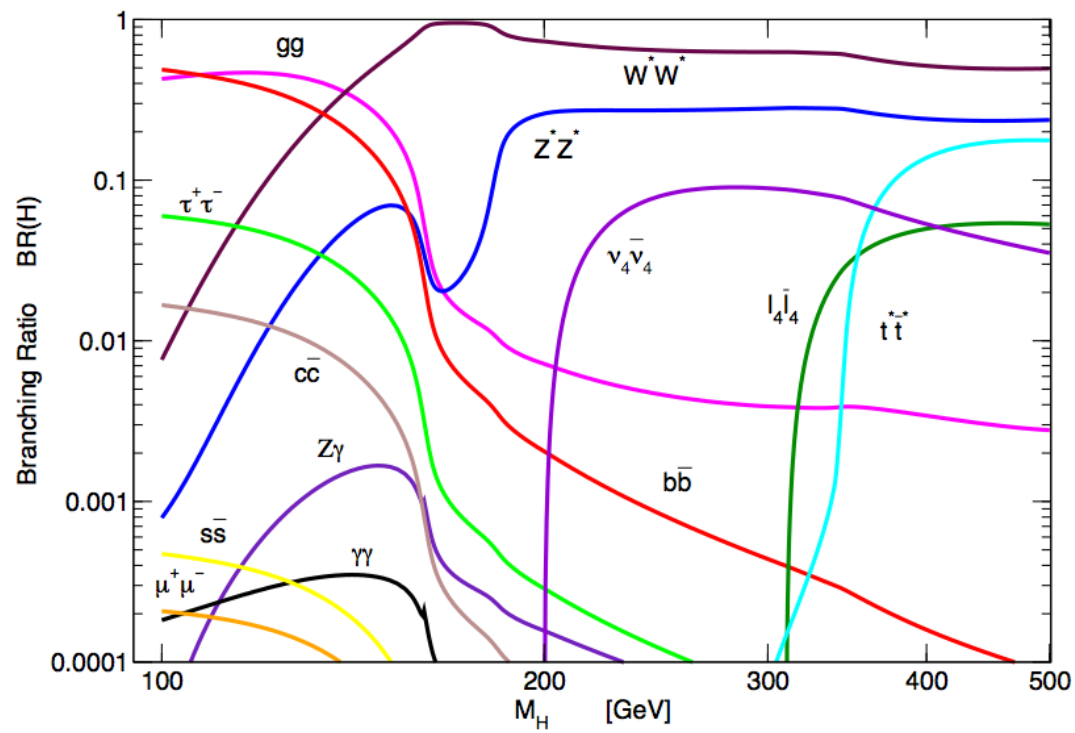
A bit of an excess (2σ at m_H=125 GeV) seen in H→$\gamma\gamma$

Extensions to the SM: Fourth-Generation Models (SM4)



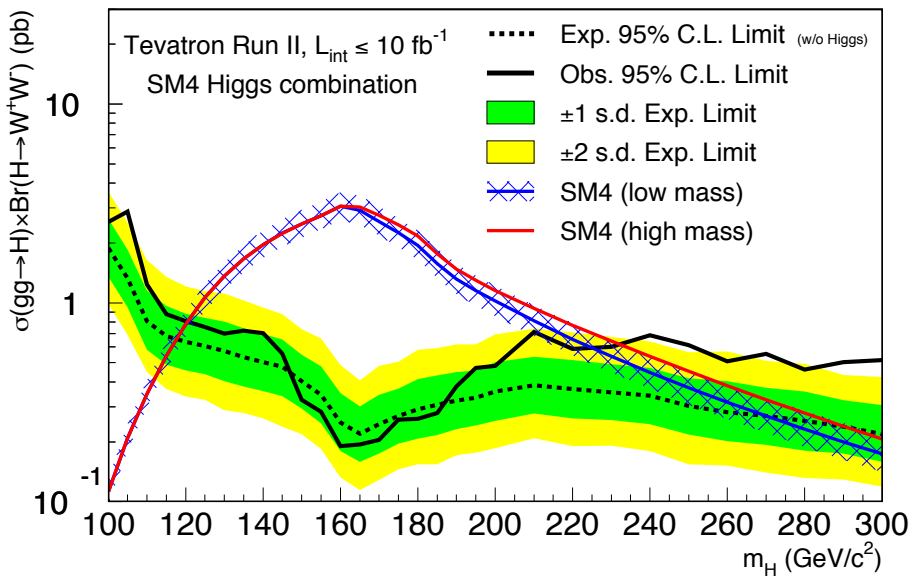
A heavy fourth generation of quarks would scale the gg→H production rate at colliders by a factor of ~9.
But watch out for $H \to \nu_4 \nu_4$ decays.
E. Arik et al., Acta Phys. Polon. B **37**, 2839 (hep-ph/0502050)





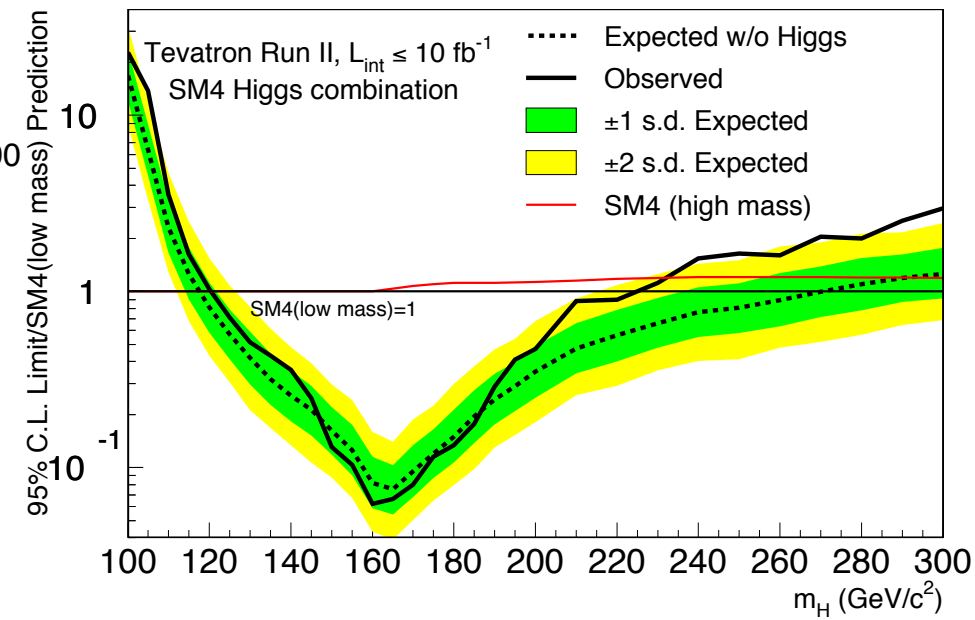
Kribs, Spannowsky, Plehn, Tait, Phys. Rev. D **76**, 075016 (2007)

Searches for gg→H→WW – Model Independent and SM4 interpretation



Searches optimized specifically for gg→H (NN's not trained with WH, ZH, or VBF).

Limit on cross section times b.r. shown along with SM4 model predictions.



Low-Mass scenario: m_{l4}=100 GeV, m_{v4}=80 GeV
High-Mass scenario: m_{l4}=m_{v4}=1 TeV
Both Scenarios: m_{d4}=400 GeV, m_{u4}=450 GeV

Note: m_{v4} lower bound is from L3's unstable 4th generation neutrino search.
P. Achard et al., PLB **517**, 75 (2001). A stable v_4 could be lighter. K. Belotsky et al., PRD **68**, 054027 (2003).

SM4 Cross Sections computed at NNLO in QCD
by Anastasiou, Boughezal, and Furlan, JHEP **1006**, 101 (2010)

Low-mass scenario exclusions:
Expected exclusion: 118 < m_H < 270 GeV/c^2
Observed exclusion: 121 < m_H < 225 GeV/c^2

A Test of the Fermiophobic Higgs Model

Model tested: Assume SM-like behavior for the Higgs boson, except switch off all couplings to fermions.

Decays for H→bb, H→ττ, and H→gg are highly suppressed. gg→H production is neglibly small.

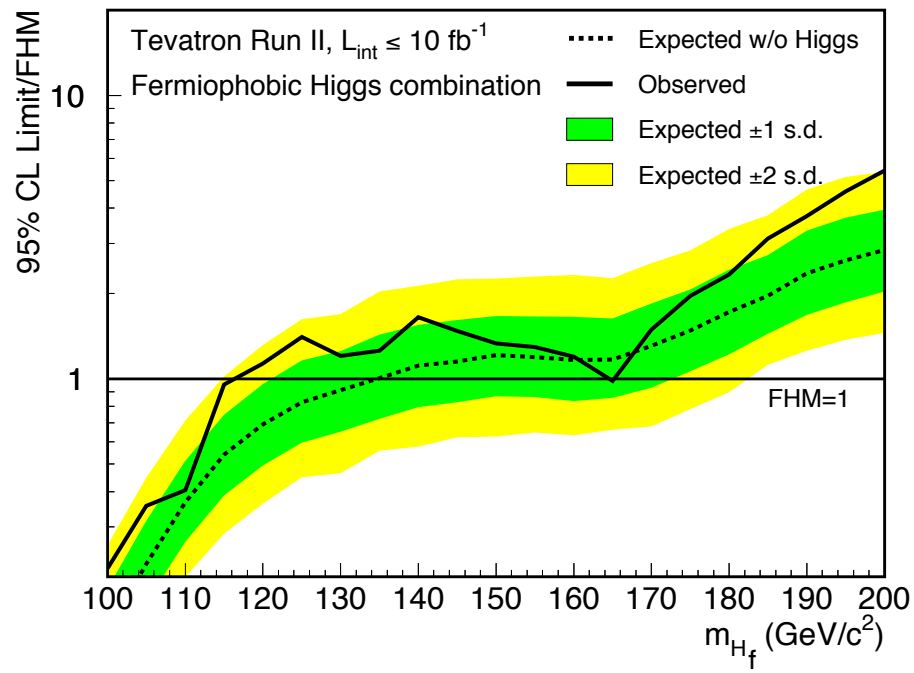
Included channels: H→γγ, H→WW, H→ZZ→4l

WH, ZH, VBF production cross sections are as predicted by the SM

H→WW, ZZ partial widths are as predicted by the SM.

H→γγ is modified – loss of the fermion loop increases the decay rate.
H→γγ search is re-optimized for this search because the p_T spectrum of the H is harder in WH and ZH than for gg→H

Branching ratios recomputed using the modified decay widths.



Observed exclusion: $100 < m_H < 116$ GeV/c^2
Expected exclsuion: $100 < m_H < 135$ GeV/c^2

Constraining the Couplings of the Higgs Boson to Fermions and Gauge Bosons

We follow the procedures and notation of the LHC Higgs Cross Section WG
A. David et al., arXiv:1209.0040

The model: SM-like, but

Hff couplings are scaled together by κ_f

HWW coupling is scaled by κ_W
HZZ coupling is scaled by κ_Z

For some studies, we scale the HWW and HZZ couplings by $\kappa_W=\kappa_Z=\kappa_V$

Standard Model: $\kappa_f = \kappa_W = \kappa_Z = 1$

Constraining Couplings

Step 1: Scale cross sections for each process according to couplings

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

$$\sigma(WH) = \sigma_{SM}(WH)\kappa_V^2$$

$$\sigma(ZH) = \sigma_{SM}(ZH)\kappa_V^2$$

LO relations, but mostly true at higher order (most QCD affects the colored initial-state particles. There is gg→WH at higher order, however.)

$$\sigma(VBF) = \sigma_{SM}(VBF)\kappa_V^2$$

A. David *et al.*, LHCHXSWG-2012-001. arXiv:1209.0040

Constraining Couplings

Step 2: Recompute all Higgs boson decay branching ratios from scaled partial widths

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

$$\Gamma(H \to W^+W^-) = \Gamma_{SM}(H \to W^+W^-)\kappa_V^2$$

$$\Gamma(H \to b\bar{b}) = \Gamma_{SM}(H \to b\bar{b})\kappa_f^2$$

$$\Gamma(H \to \tau^+\tau^-) = \Gamma_{SM}(H \to \tau^+\tau^-)\kappa_f^2$$

$$\Gamma(H \to c\bar{c}) = \Gamma_{SM}(H \to c\bar{c})\kappa_f^2$$

$$\Gamma(H \to ZZ) = \Gamma_{SM}(H \to ZZ)\kappa_V^2$$

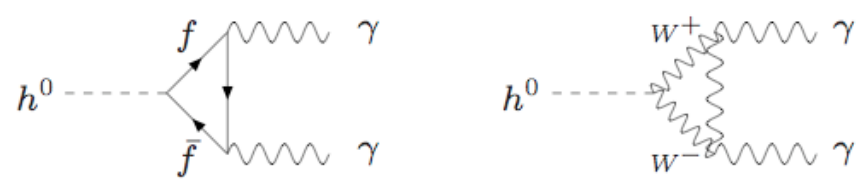
$$\Gamma(H \to \gamma\gamma) = \Gamma_{SM}(H \to \gamma\gamma)\left|\alpha\kappa_V + \beta\kappa_f\right|^2$$

Other modes, like $H \to \mu^+\mu^-$ and $H \to Z\gamma$ have very small widths

$$Br(H \to X\bar{X}) = \frac{\Gamma(H \to X\bar{X})}{\sum_i \Gamma_i}$$

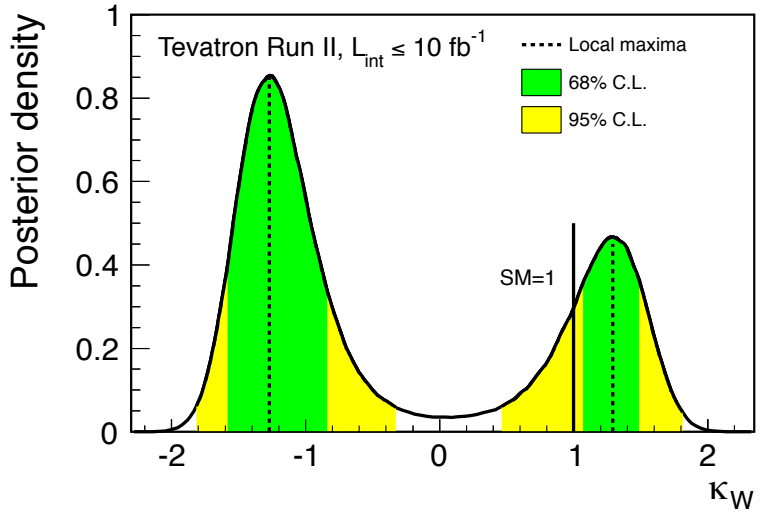
α and β come from Spira et al., arXiv:hep-ph/9504378

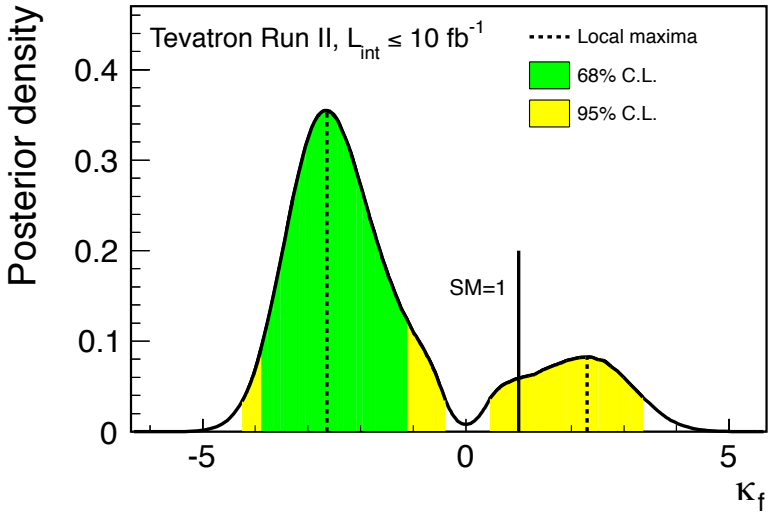
α=1.28 β = -0.28

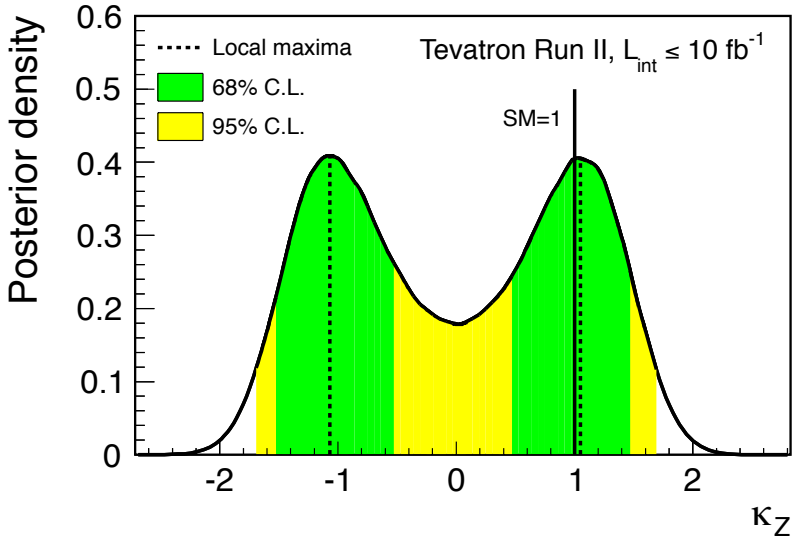


Posterior Constraints on Coupling Scalings

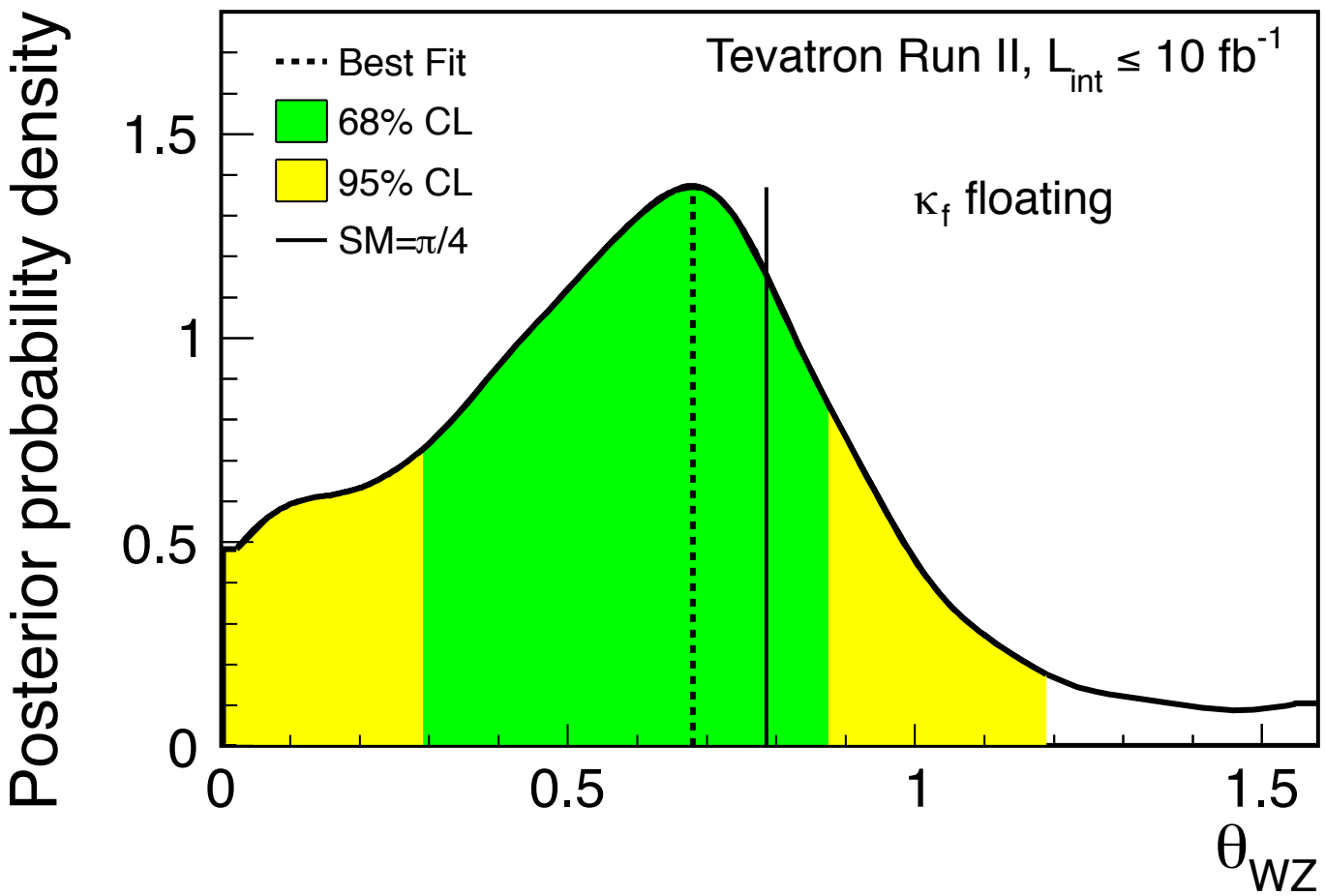
- Uniform priors assumed.
- Coupling scalings not shown are fixed to their SM values



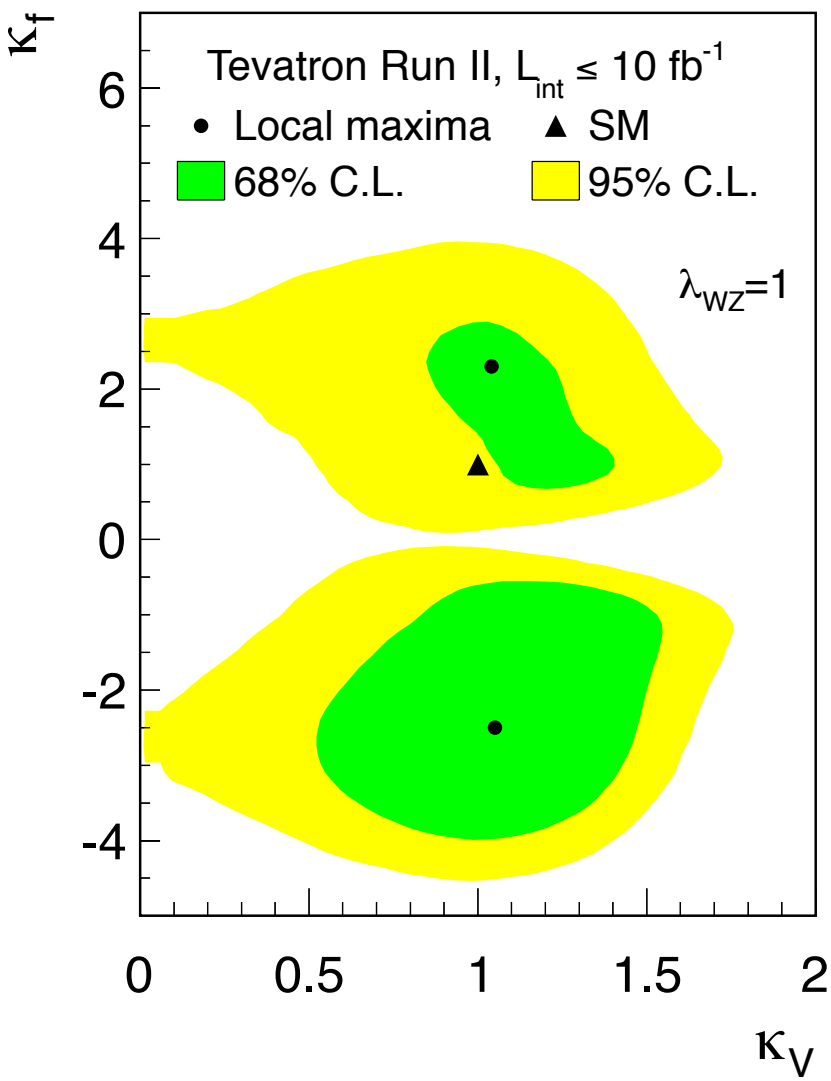


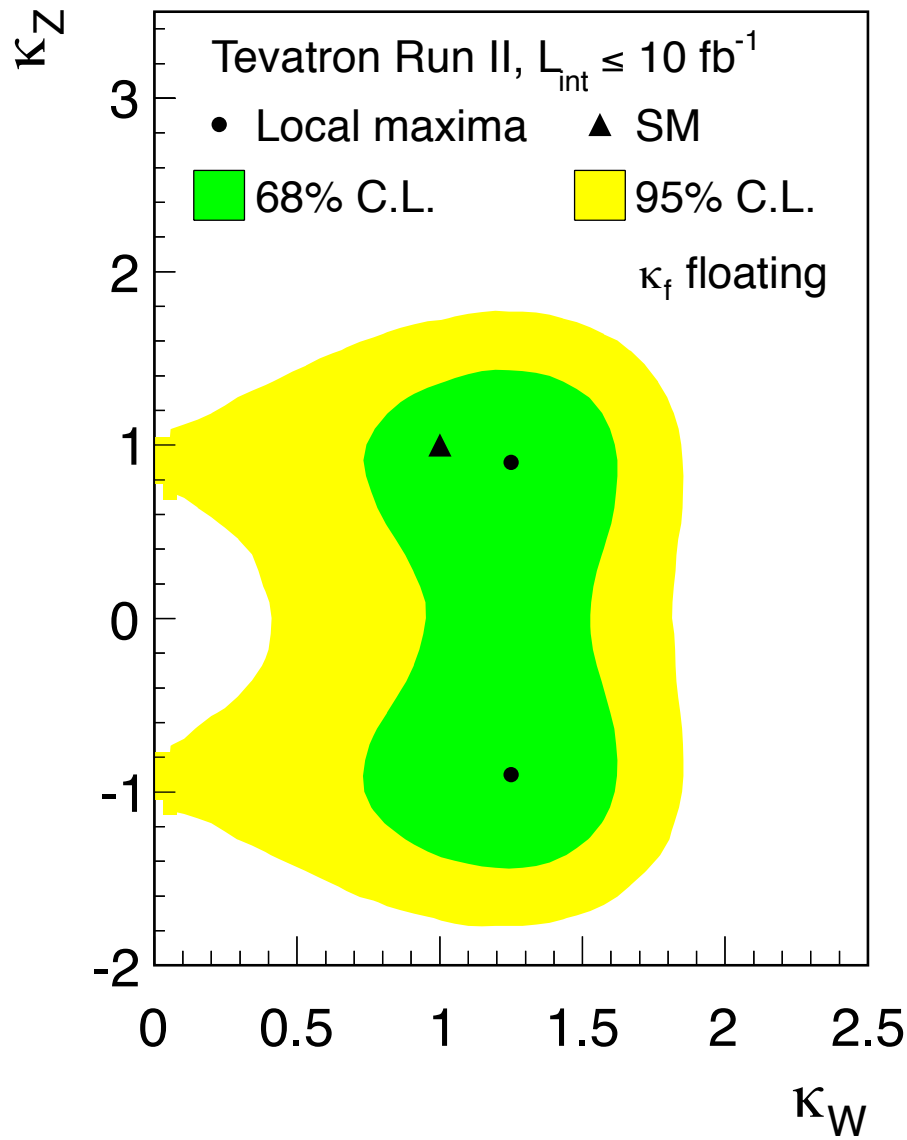


Excess in the H→γγ searches drives the asymmetry from positive and negative coupling scale factors


Posterior probability density
Best Fit
68% CL
95% CL
SM=π/4
Tevatron Run II, $L_{int} \leq 10\ fb^{-1}$
κ_f floating
0
0.5
1
1.5
0
0.5
1
1.5
θ_{WZ}

Two-Dimensional Coupling Parameter Constraints





Summary

The Tevatron sees an excess of events consistent in all decay channels with the SM-Higgs-like particle observed at the LHC near m_H=125 GeV/c^2. Significance: 3.1σ at m_H=125 GeV/c^2.

The Higgs boson does not look like that of the Fermophobic model or the SM with a fourth generation.

Higgs boson couplings to W, Z, and fermions are consistent with SM predictions

Extracting coupling information from the data requires full predictions of signal rates and shapes in all discriminants of all channels.

Channels that contribute little to the total SM sensitivity can have outsized impacts on exotic coupling scenario tests.