Final Combination of CDF's Searches for the Higgs Boson

in the Standard Model and Extensions

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Fermilab

On behalf of the CDF Collaboration

Joint Experimental-Theoretical Physics Seminar
January 18, 2013

Tevatron Performance

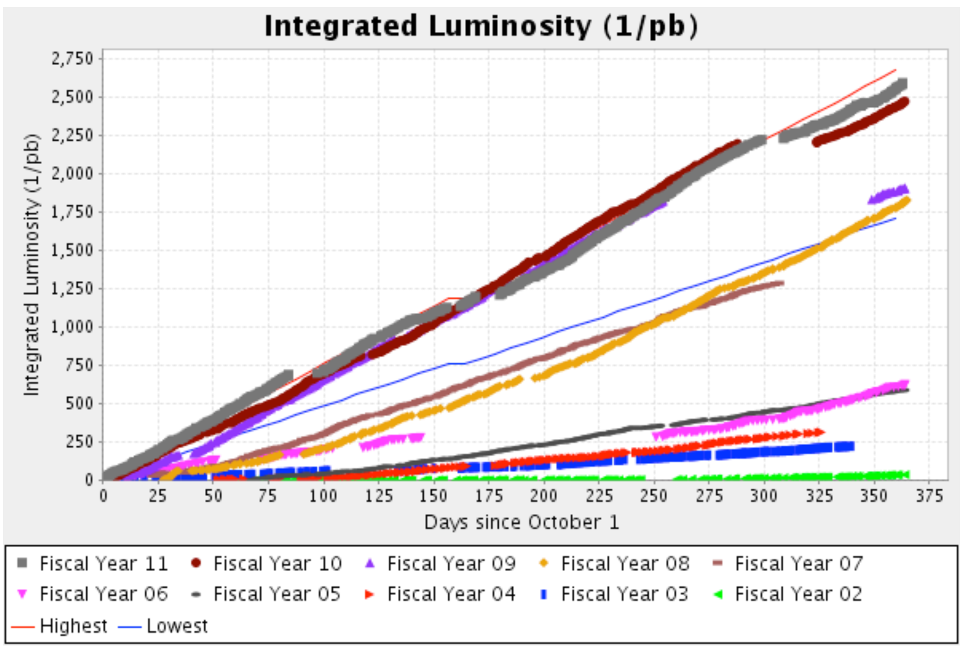
Proton-antiproton collisions with

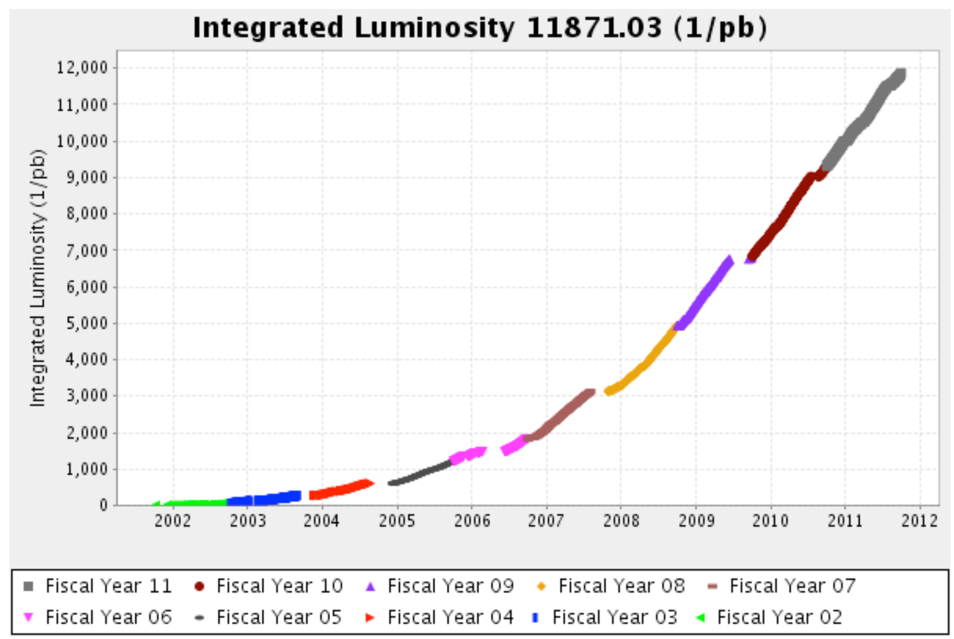
Run I: 1988 – 1996 :   CDF Collects over 100 pb^{-1} of data at E_{CM} = 1.8 TeV

Run II: 2001 – 2011 :   CDF Collects 10.0 fb^{-1} of data at E_{CM} = 1.96 TeV

-- 12 fb^{-1} delivered.

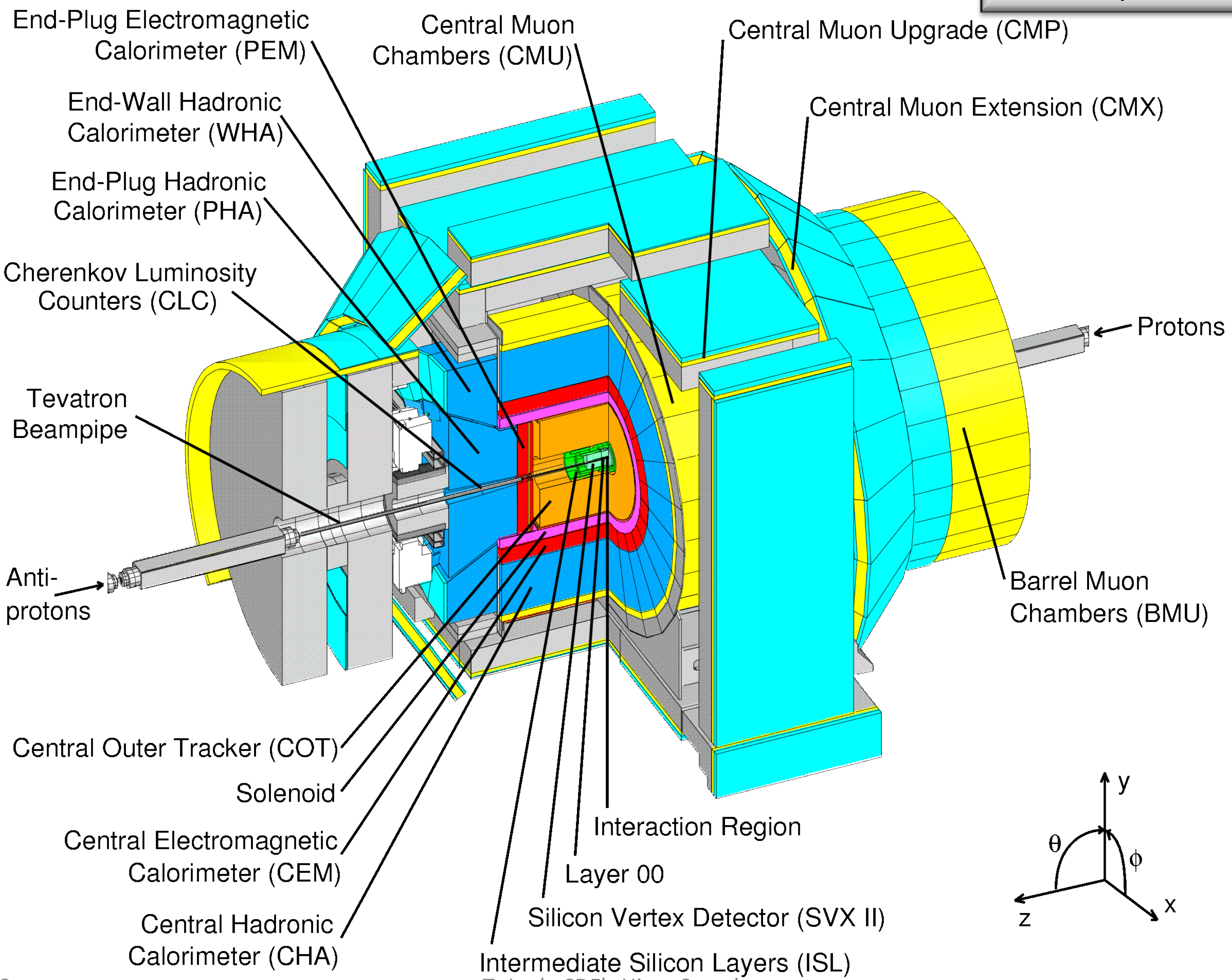
Many thanks to the Beams Division for spectacular performance of the Tevatron



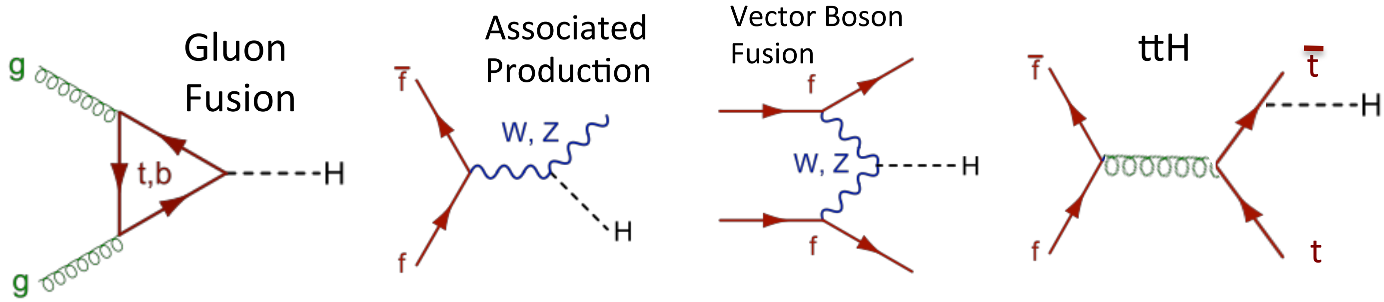


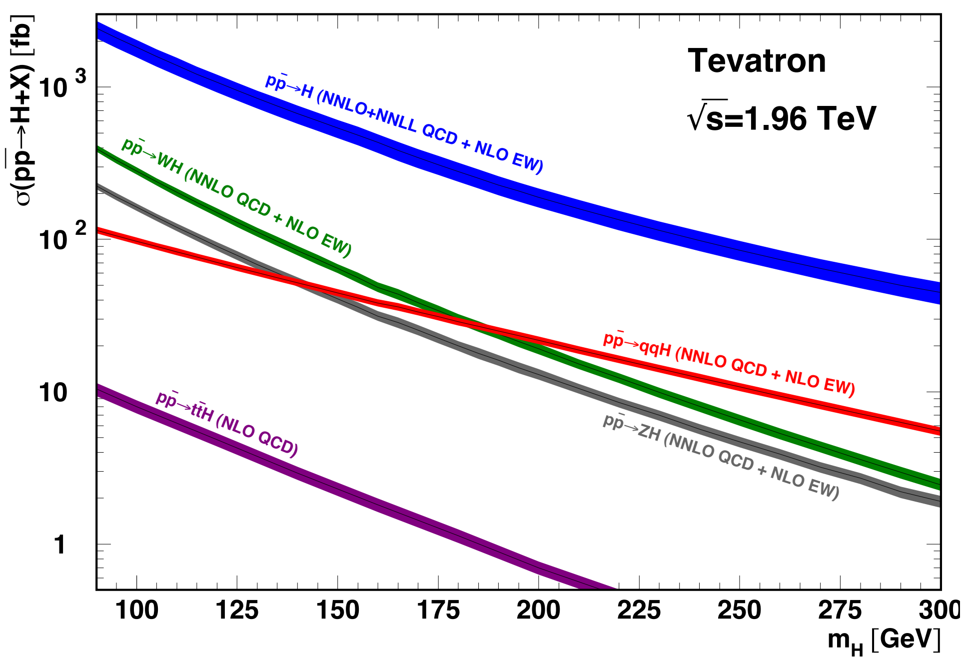
The CDF II Detector

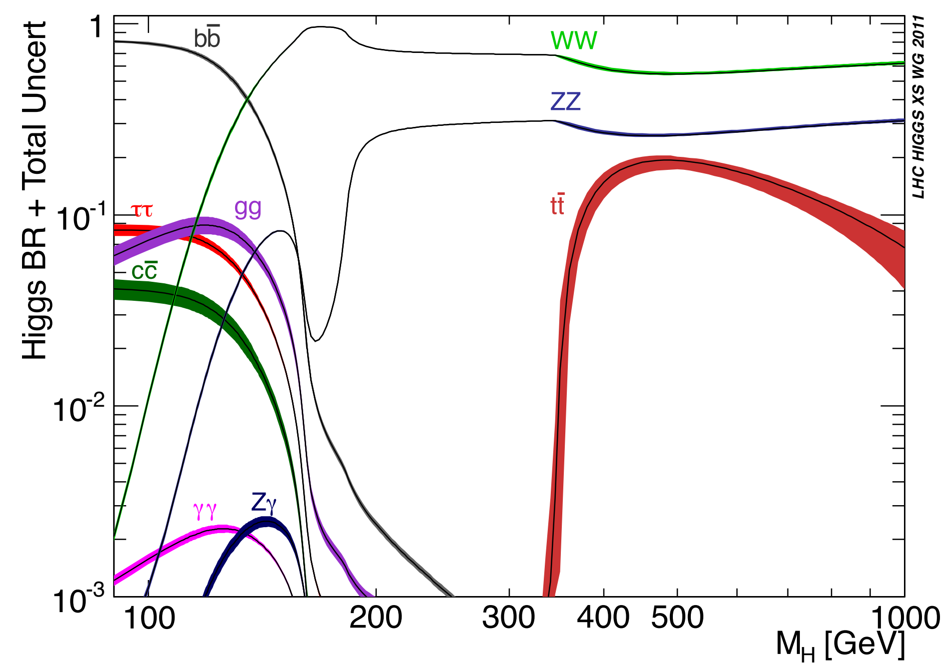
First CDF $p\bar{p}$ event: 1985
End of operations: 2011



SM Higgs Boson Production and Decay Rates







Primary analysis modes:

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

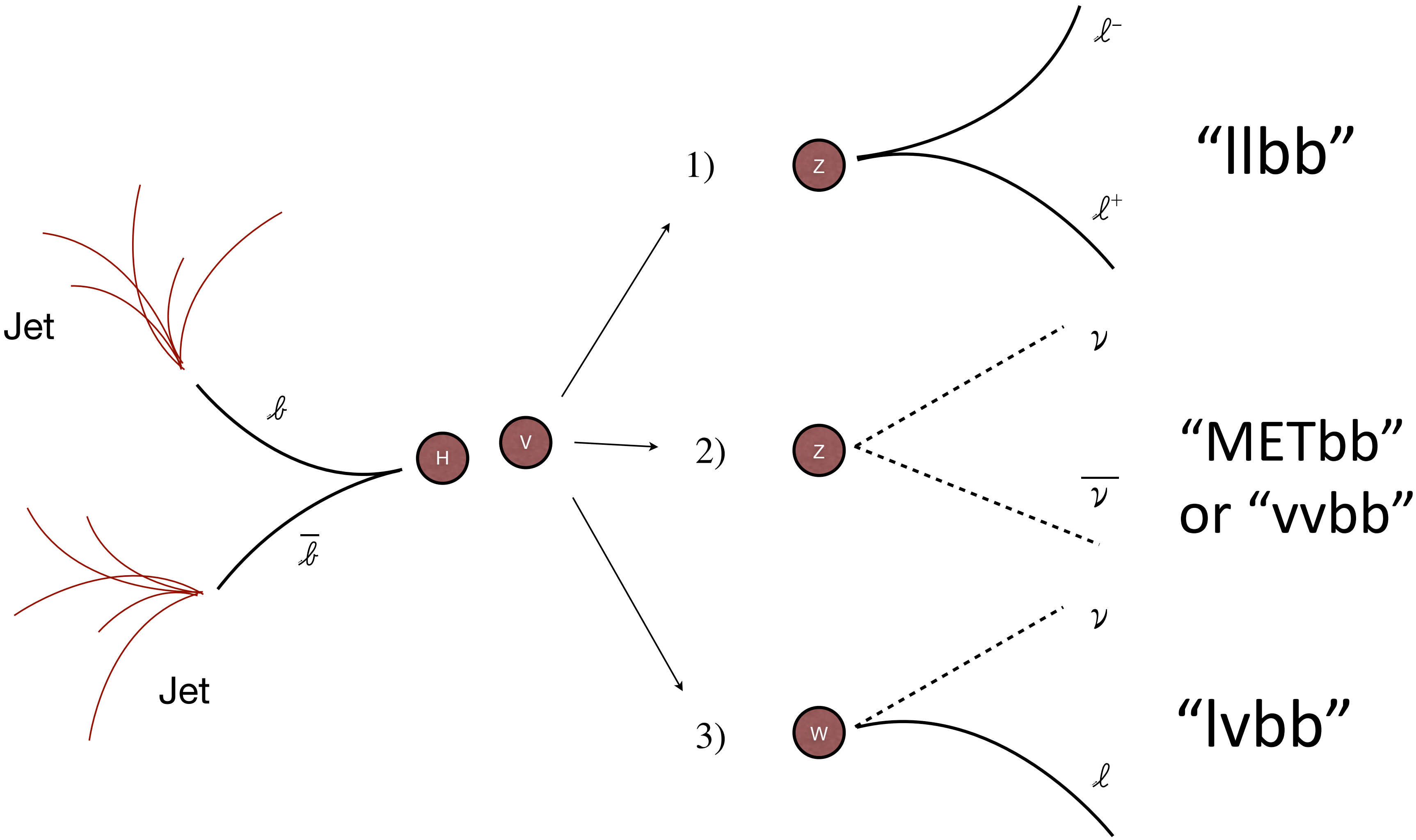
Additional modes:

H→ττ, H→γγ, H→ZZ→4l
ttH→ttbb

Talk Outline

- Updates to CDF's METbb Search
- CDF's H→bb combination
- Combined Results of all CDF
  SM Higgs boson searches
- Fourth-Generation and
  Fermiophobic Results
- Constraints on non-SM Couplings

The Main Associated Production Search Channels



Drawing Credit: CMS Higgs TWiki.

CDF also seeks qqH→qqbb and ttH→ttbb

The Status as of 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)

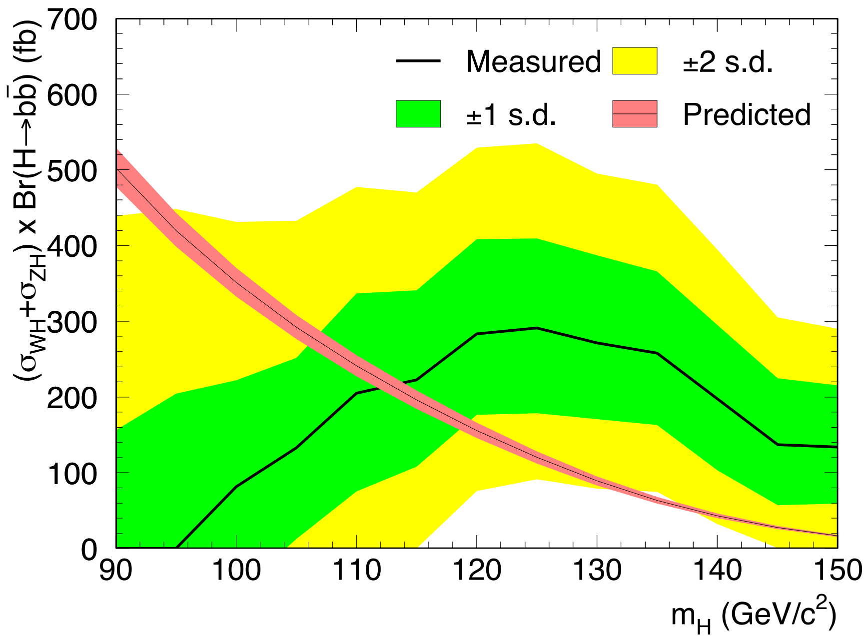
D0 lvbb: Phys. Rev. Lett. **109**, 121804 (2012)
D0 llbb: Phys. Rev. Lett. **109**, 121803 (2012)
D0 METbb: Phys. Lett. B **716**, 285 (2012)

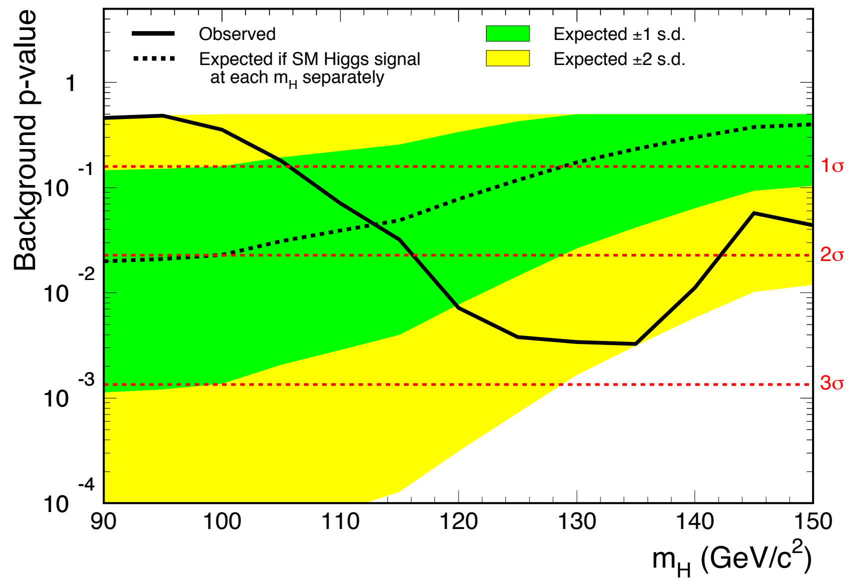
D0 Combined H→bb: Phys. Rev. Lett. **109**, 121802 (2012)

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

CDF's H→bb Results, Summer 2012

Phys. Rev. Lett. **109**, 111802 (2012)





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

$$\sigma(WH+ZH)\times Br(H\rightarrow b\bar{b}) = 291^{+118}_{-113} \text{ fb}$$

The SM prediction is

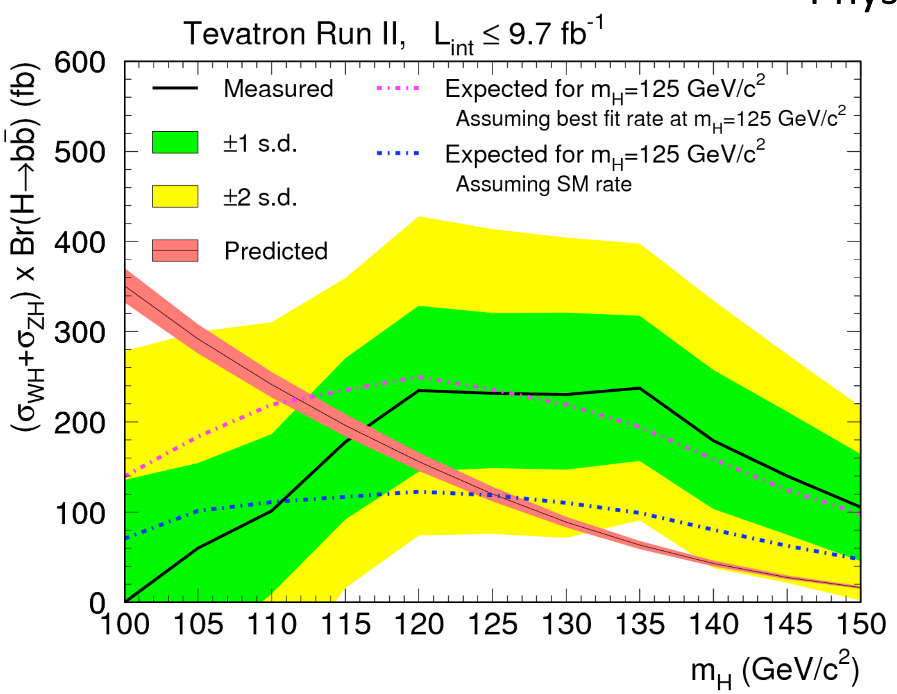
$$\sigma(WH+ZH)\times Br(H\rightarrow b\bar{b}) = 120 \pm 8 \text{ fb}$$

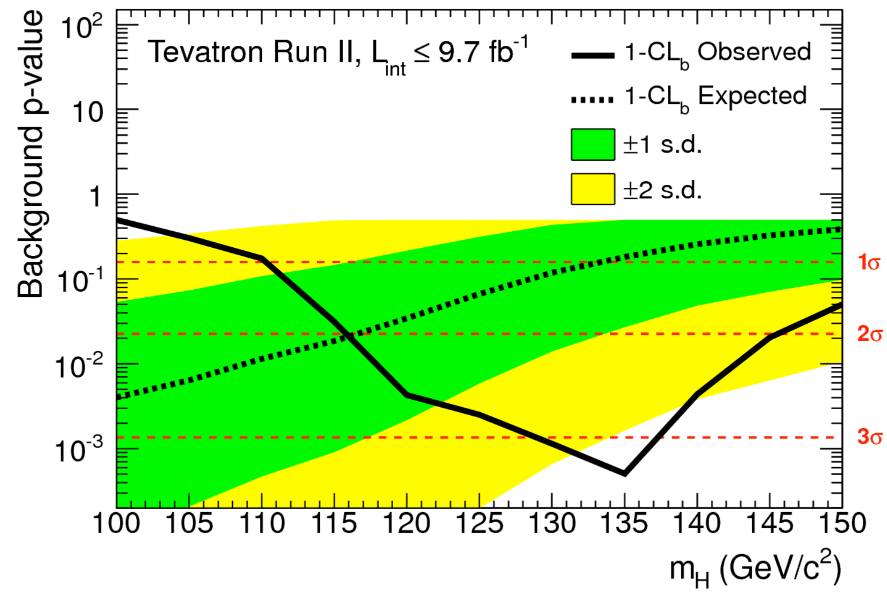
p-value using the cross section as test statistic: 2.7σ

Cross Sections: Baglio, Djouadi; Harlander, Mantler, Marzani, Ozeren
Branching Ratios: LHC Cross Section Working Group
Denner et al., arXiv:1101.0593, arXiv:1201.3084

Tevatron H→bb Results, Summer 2012

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





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

$$(\sigma_{WH} + \sigma_{ZH}) \times B(H \to b\bar{b}) = 230^{+0.090}_{-0.080}\ \text{(stat+syst) fb}$$

SM Prediction: 0.12 ± 0.01 pb

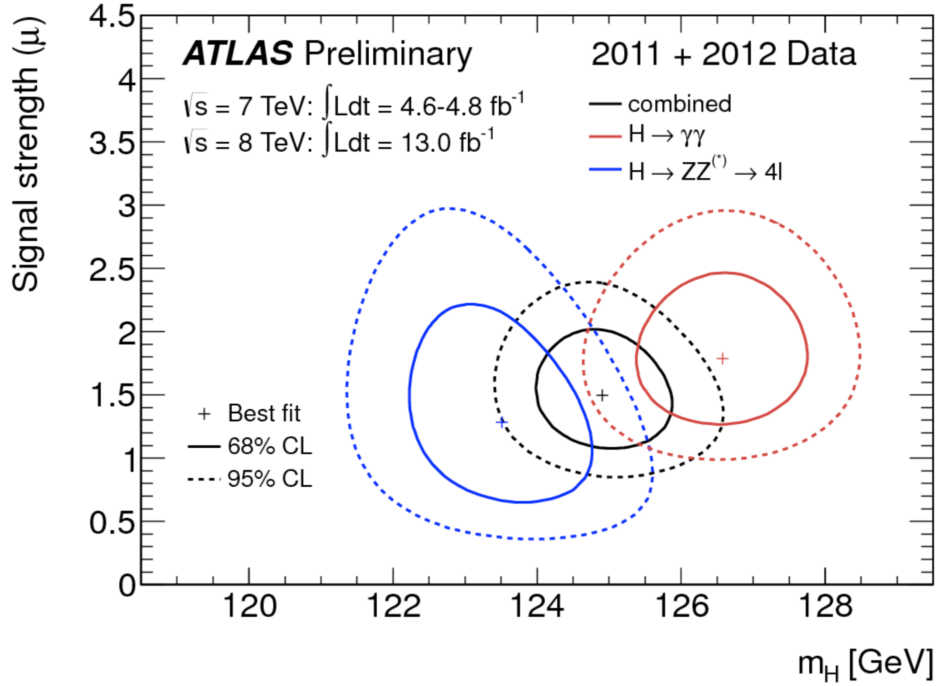
Maximum local significance: 3.3σ at m_H=135 GeV/c^2

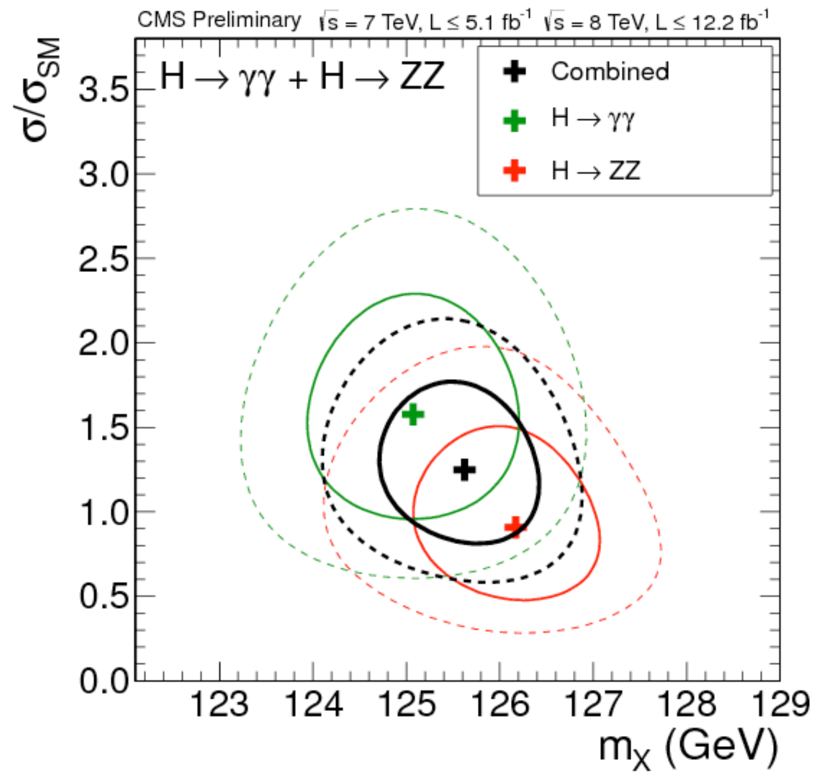
Global significance: 3.1σ

Local significane at m_H=125 GeV/c^2 is 2.8σ

Current Status from the LHC

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

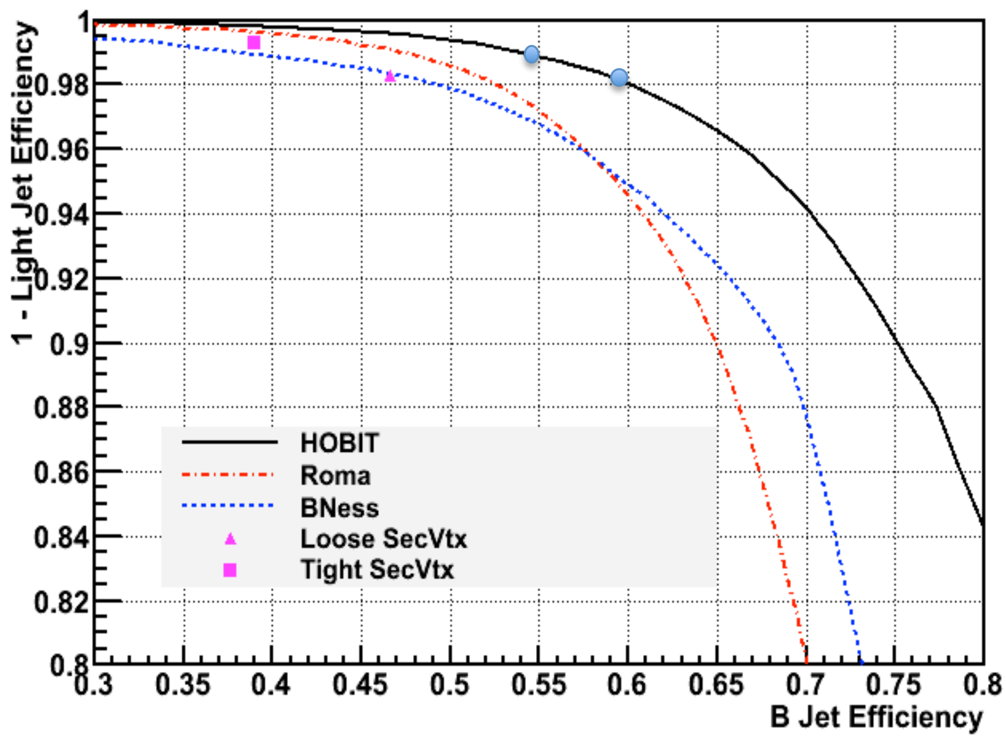




Many more superb results are available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

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

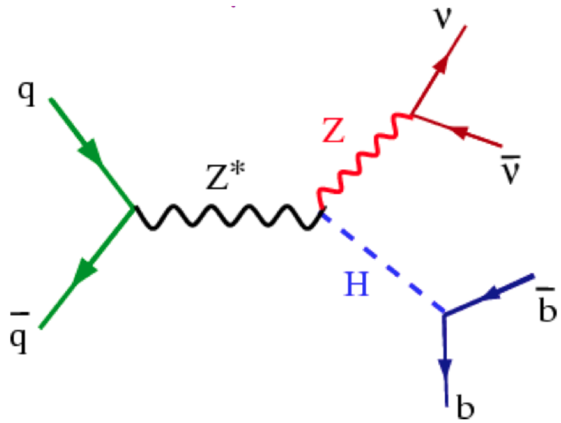
Operating Point	Mistag rate	SECVTX efficiency	HOBIT efficiency
Tight	1.4%	39%	54%
Loose	2.9%	47%	59%

per-jet efficiencies shown

J. Freeman et al., Nucl. Instrum. Methods A **697**, 64 (2012).
see also M. Stancari's JETP Seminar, Mar. 7 2012

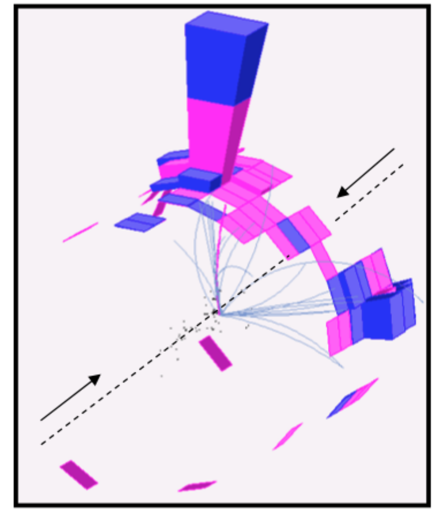
VH→METbb Analysis

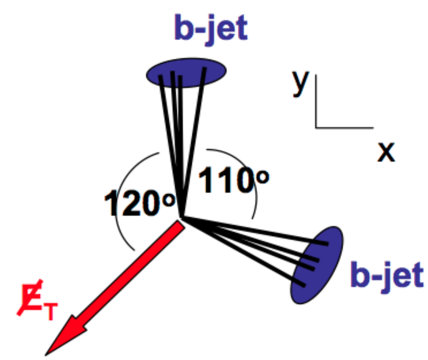
Event Preselection



Select Events with 2 or 3 jets:
$25 < E_{T,J1} < 200$ GeV
$20 < E_{T,J2} < 120$ GeV
If a third jet is present,
$15 < E_{T,J3} < 100$ GeV
$|\eta_{jet}| < 2$ with at least one jet with $|\eta|<0.9$

No identified lepton
MET > 35 GeV
$\Delta\varphi_{MET,J2}>0.4$; $\Delta\varphi_{MET,J3}>0.4$ if present





B-tagging:

Double-tight HOBIT tag (TT)
Tight tag + Loose Tag (TL)
One tight tag (1T)

Inversions of the event selection requirements define control samples

Signal (and b-tagged background) gain by using HOBIT compared with SECVTX and JetProb

Tag category	b-tagging efficiency per event	
	Ref. [5]	This analysis
Two tight b tags	13.7% (SS)	18.1% (TT)
One tight and one loose b tag	13.1% (SJ)	14.6% (TL)
Only one tight b tag	31.4% (1S)	31.6% (1T)

Categories are non-overlapping.
The 1T category does not include TL or TT events

Data-Based Tagged QCD Multijet Prediction

Control Region: Same cuts as Preselection but:

- no b-tag required
- 35 GeV < MET < 70 GeV
- $\Delta\phi$(MET,j2) < 0.4

Nearly all events are QCD multijet events in this sample.

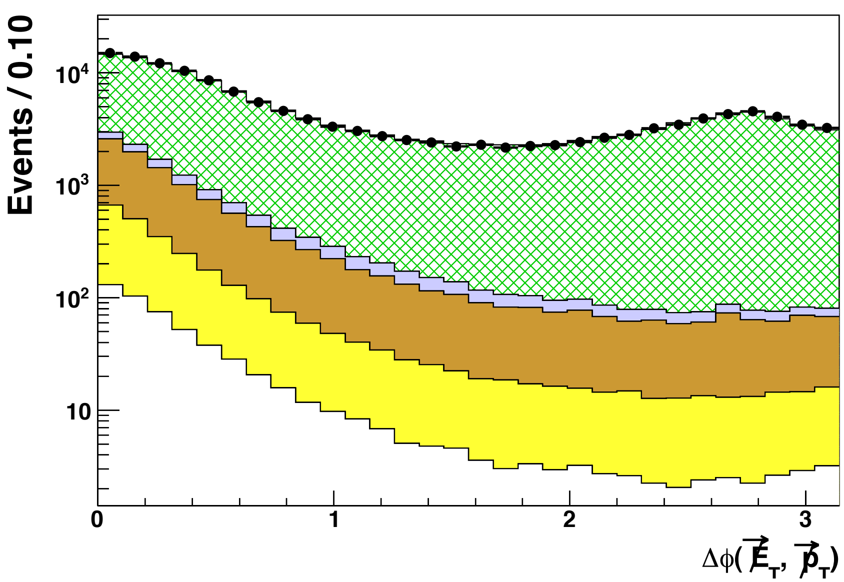
Measure tag fractions for TT, TL, 1T in this sample as functions of

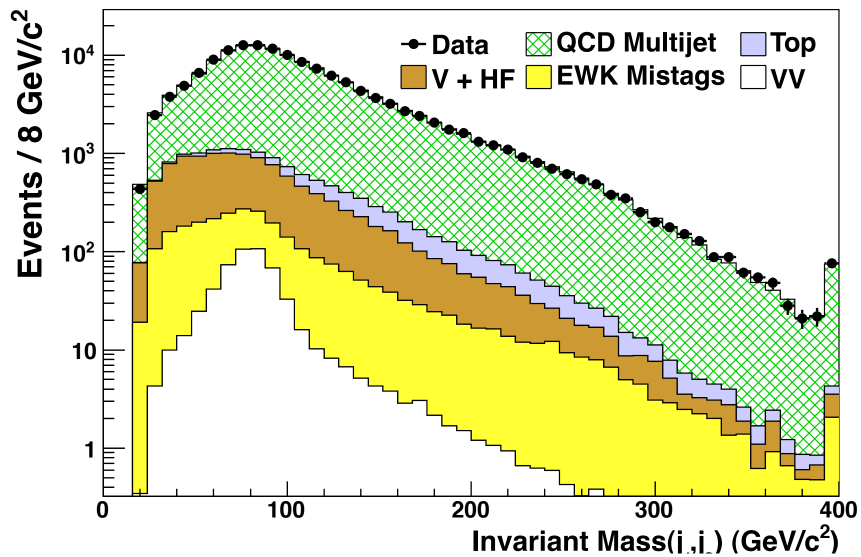
- H_T
- missing p_T
- the fraction of charged energy in the cones of jets 1 and 2
- the number of reconstructed primary vertices
- The momentum-weighted sum of the sines of the angles between reconstructed muon candidates and jet axes

} New for the HOBIT analysis

Result is three Tag Rate Matrices. Apply these to preselected data minus W+jets, Z+jets, ttbar, single top, and dibosons to model the tagged QCD multijet background

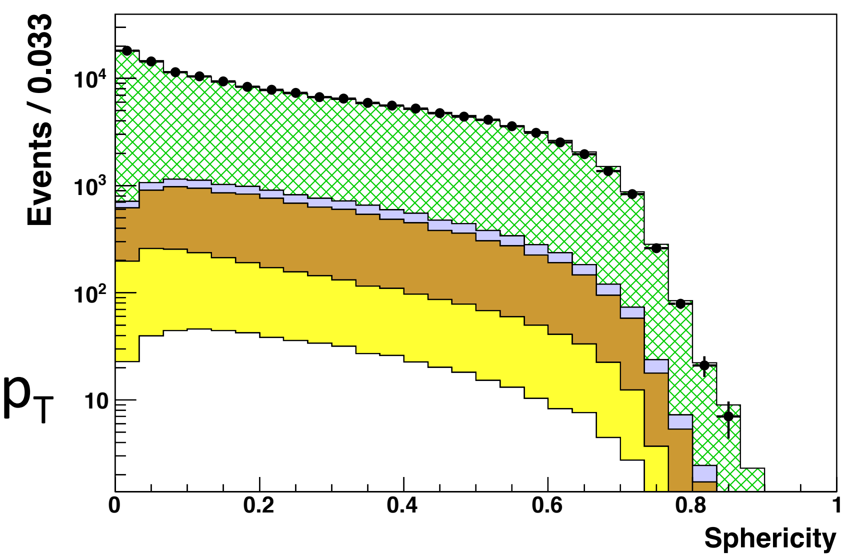
Validation of Key Variables in the Tagged Preselection Sample





Variables also checked in

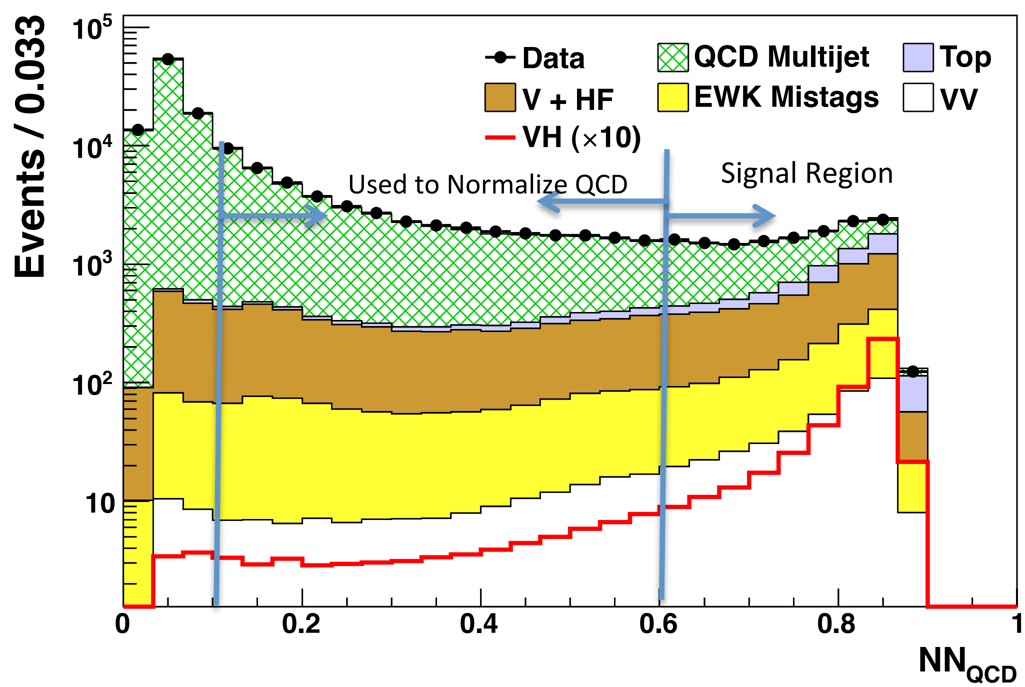
- QCD-enriched region:
  low MET, low Δϕ(MET,jet)
- Electroweak control region
  Requires the presence of a high-p_T isolated lepton (e or μ)



QCD-rejection Neural Network

NN_{QCD} Inputs
$M(\not{\vec{E}}_T, \vec{j}_1, \vec{j}_2)$
$\not{E}_T$
$\not{p}_T^{tr}$
$\not{H}_T / \not{E}_T$
$\not{E}_T / H_T$
$\Delta\phi(\not{\vec{E}}_T, \not{\vec{p}}_T^{tr})$
$\max(\Delta R(\vec{j}_i, \vec{j}_j))$ where $i \neq j$
$\max(\Delta\phi(\vec{j}_i, \vec{j}_j))$ where $i \neq j$
$\max(\Delta\phi(\not{\vec{E}}_T, \vec{j}_i))$
$\max(\Delta\phi(\not{\vec{p}}_T^{tr}, \vec{j}_i))$
θ^* of jet in 2-jet rest frame
Sphericity

TT+TL+1T together



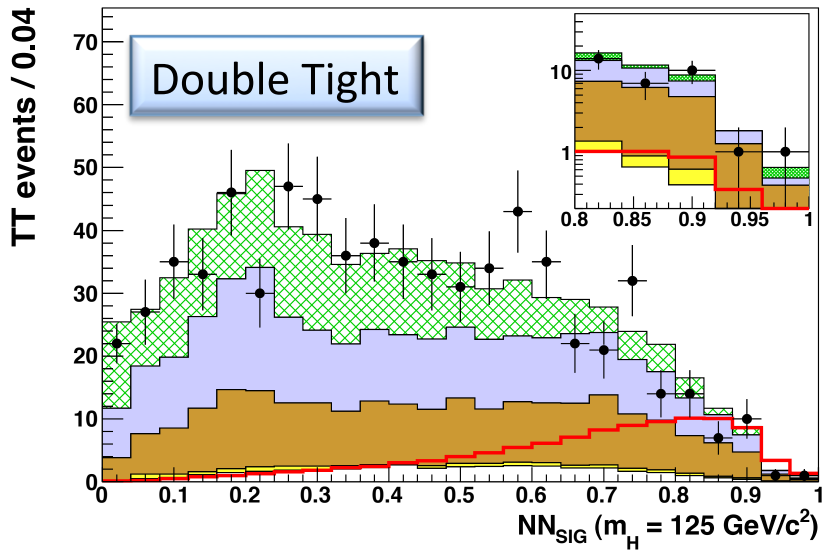
Signal Region: NN_{QCD}>0.6. Retains 87% of signal while rejecting 90% of QCD multijet backgrounds

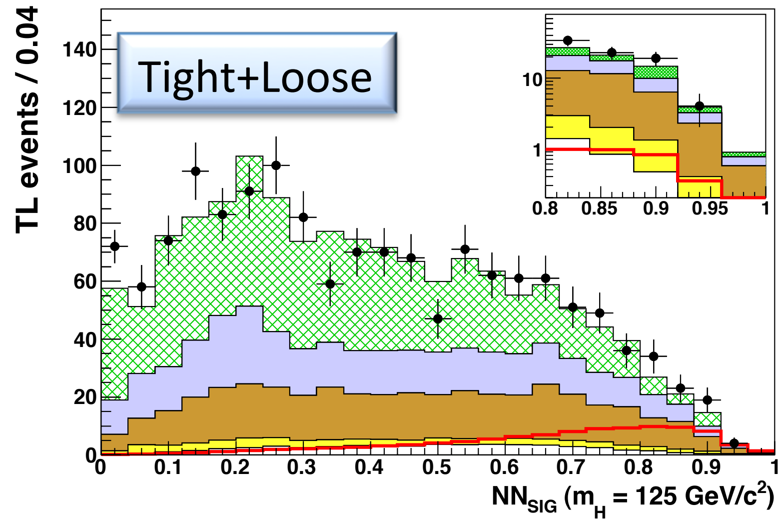
0.1 < NN_{QCD} < 0.6 events used to normalize the QCD rate
Extrapolation uncertainties assessed in predicting rates for NN_{QCD} > 0.6. Larger uncertainties than Moriond 2012 analysis

Predicted Yields in the Three Tagged Signal Samples

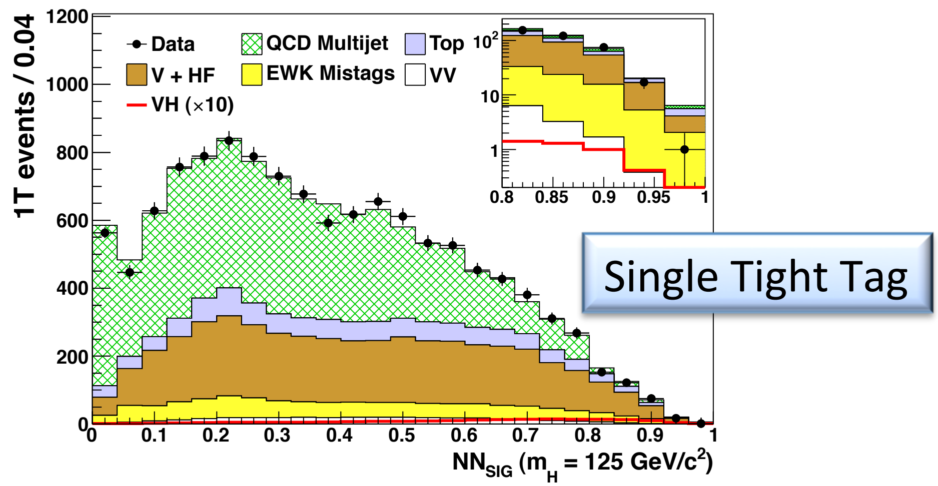
Process	1T	TL	TT
QCD Multijet	5941 ± 178	637 ± 25	222 ± 16
Top	1174 ± 158	302 ± 40	271 ± 34
V+heavy flavor jets	3124 ± 718	286 ± 83	211 ± 65
Electroweak mistags	1070 ± 386	55 ± 21	13 ± 6
Diboson	305 ± 46	48 ± 6	41 ± 5
Total expected background	11612 ± 949	1329 ± 112	759 ± 86
Observed Data	11955	1443	692
ZH→ννbb, llbb (m_H=125 GeV)	9.7 ± 1.0	5.4 ± 0.5	5.4 ± 0.5
WH→lνbb	9.8 ± 1.0	5.3 ± 0.5	5.3 ± 0.5

Signal-Separation Neural Network Output Distributions for the Three b-tagged Signal Samples



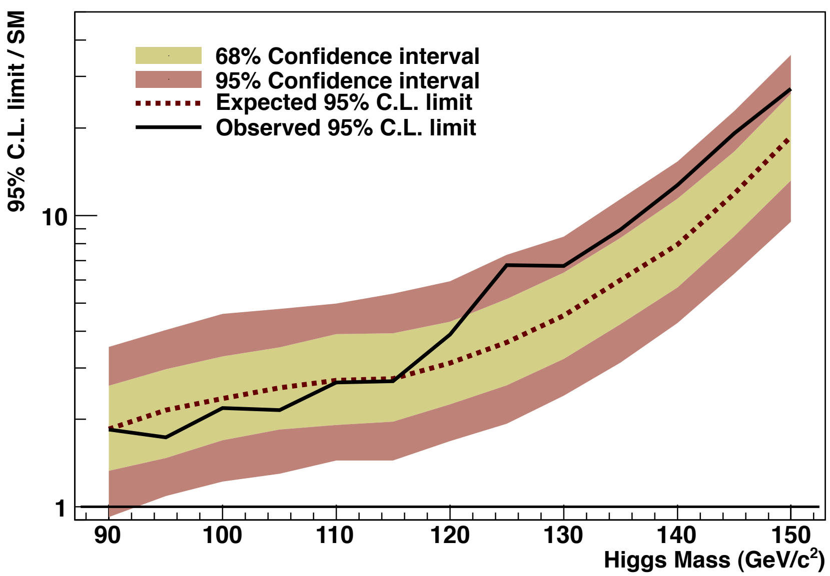


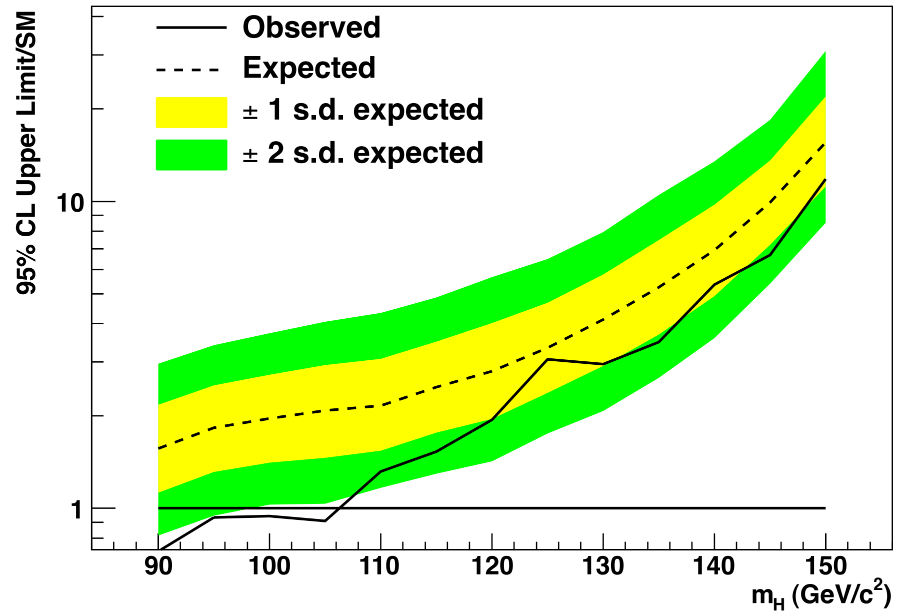
$\mathrm{NN_{SIG}}$ Inputs
$M(\vec{\not\!\!E}_T, \vec{j}_1, \vec{j}_2)$
$M(\vec{j}_1, \vec{j}_2)$
$H_T - \not\!\!E_T$
$\vert\vert \vec{\not\!\!H}_T - \vec{\not\!\!E}_T \vert\vert$
Output of TrackMET neural network
Output of $\mathrm{NN_{QCD}}$
$\max(\Delta R(\vec{j}_i, \vec{j}_j))$ where $i \neq j$



Observed and Expected Limits

Phys. Rev. Lett. **109**, 111805 (2012)





SECVTX+JP
SS+SJ+1S

At m_H=125 GeV,
obs = 6.7xSM
exp = 3.6xSM

This Result:
HOBIT TT+TL+1T

At m_H=125 GeV,
obs = 3.06xSM
exp = 3.33xSM

8% sensitivity improvement at m_H=125 GeV/c^2.
Average expected improvement over whole mass range: 14%.

Big change in observed result!
New limit is a drop of 55% relative to the published one at m_H=125 GeV/c^2

Discussion of METbb Results

Many cross-checks run to assess compatibility of the new HOBIT result and the published SECVTX+JetProb result:

1. Reanalysis of 1S, SJ, and SS tag categories using new framework, selection, and systematics
2. Validation of b-jet tagger modeling
3. Effects of Data Migration
4. P-value for the difference in observed limits using pseudoexpriments
5. Background modeling

Analysis Updates Besides Changing b-Taggers

- B-tag scale factor uncertainty handling improved – proper anticorrelations between exclusive samples evaluated.

- QCD Multijet uncertainties are larger, and improved methods for extrapolating from the control regions are used.

- Events with with jets with E_{T1}>200 GeV and E_{T2}>120 GeV now rejected

- Additional MET cut at 35 GeV in early stage of analysis to get away from trigger turn-on now applied

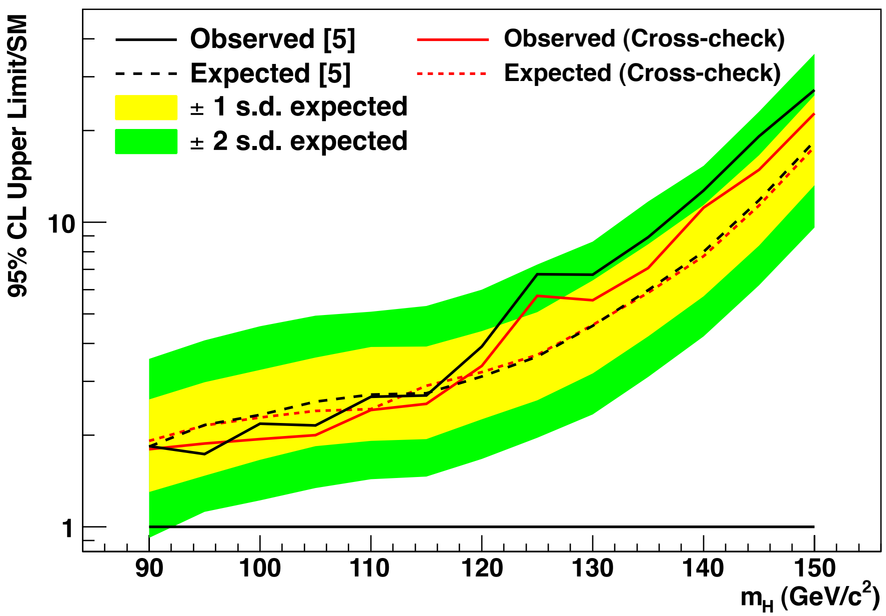
- V+heavy flavor jets backgrounds now itemized separately with independent sources of uncertainty. The charm tag rate and gluon splitting rates are different depending on the sample.

- Z+jets with Z→bb background model included.

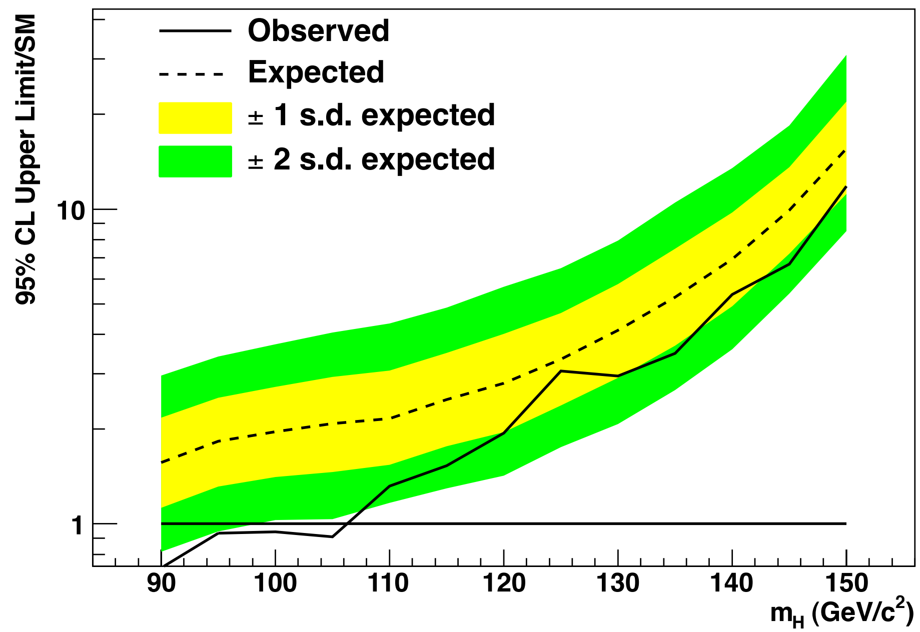
Re-Doing the SECVTX+JetProb analysis with these changes measures the impact of the changes and provides a cross check of the Winter/Summer 2012 METbb analysis

Results of SECVTX+JetProb Redo Cross Check

SECVTX+JP Published analysis
+ Redo Crosscheck



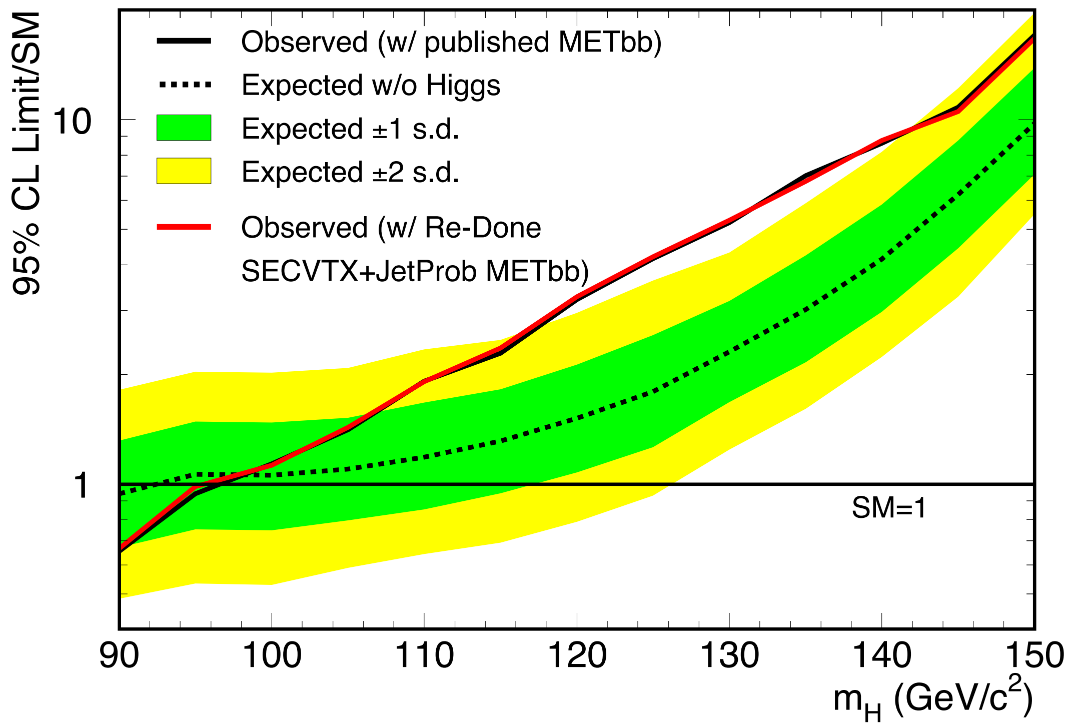
HOBIT



At m_H=125 GeV/c^2, the observed HOBIT limit is **47%** lower than the Re-Done SECVTX+JP observed limit.
(Was 55% lower than published).

Combine the Redone SECVTX+JetProb METbb with llbb+lvbb

CDF Combined VH→Vbb limits/SM



Black Curve:
Same limit curve as in
Phys. Rev. Lett. **109**, 111802 (2012)

Red Curve:
Published llbb, lvbb, and the Redone SECVTX+JetProb crosscheck

P-value remains unchanged.
at 2.7σ at m_H=125 GeV/c^2

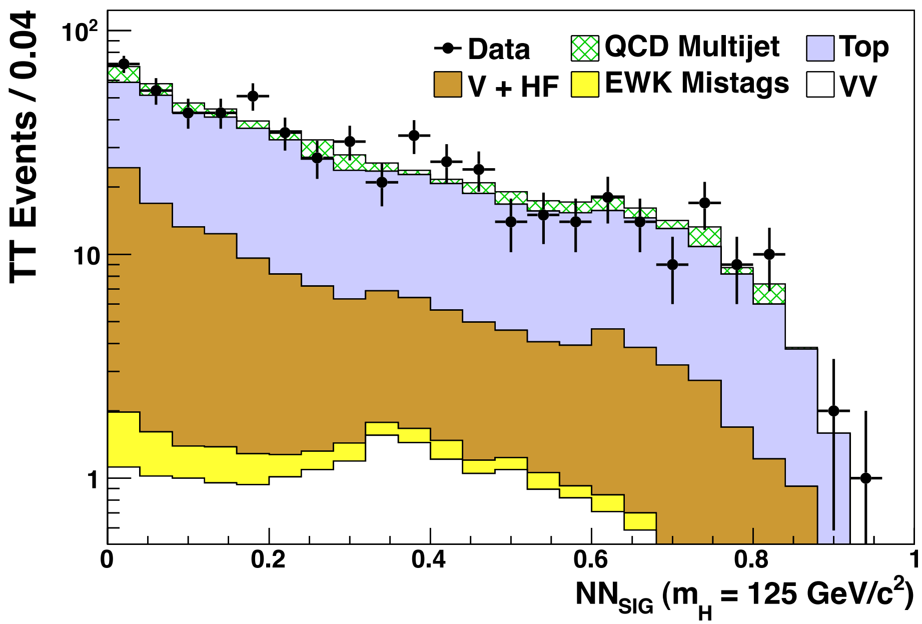
CDF finds no significant issues with the previous version of the METbb analysis and stands firmly behind last summer's published results.

B-Tag Modeling Validation: Electroweak Control Region

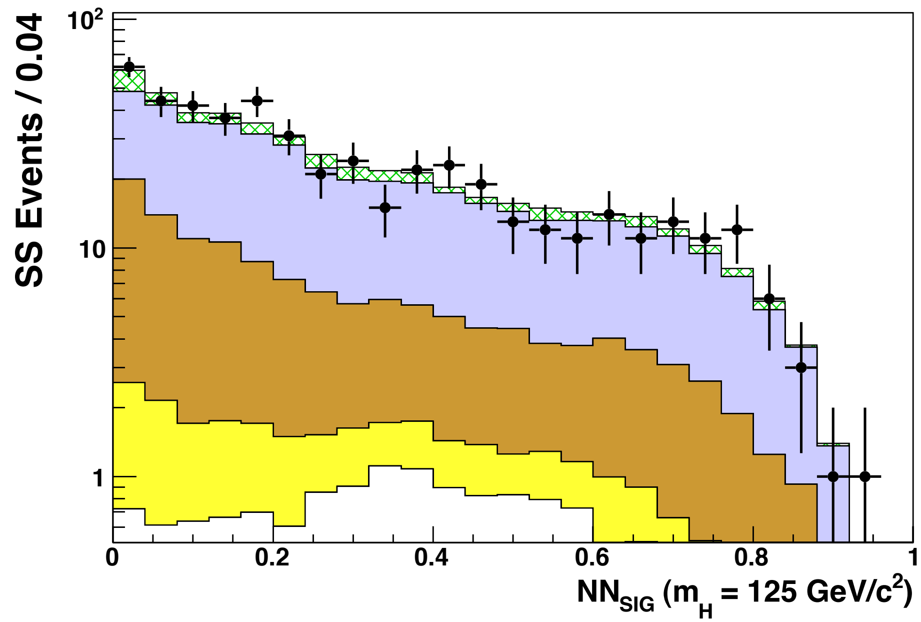
Preselection requirements, but require a high-p_T isolated lepton (e or μ)

Look for mismodeled correlations between NN_{SIG} and b-tagging

Double-Tight HOBIT TT



Double-Tight SECVTX SS



No modeling issues seen with either b-tag algorithm as a function of NN_{SIG}

Studying the Effects of Event Migration

We do not see problems in modeling: Suspect statistical fluctuations.

Data Event Overlap Fractions: $NN_{SIG}>0.8$

	1T	**TL**	**TT**
1S	55%	35%	15%
SJ	4%	20%	30%
SS	1%	14%	51%

Denominator: HOBIT analysis events

HOBIT Tagger is more efficient: Expect promotion of signal events to higher tag categories.

Event Rate Summaries – HOBIT analysis vs. SECVTX+JP

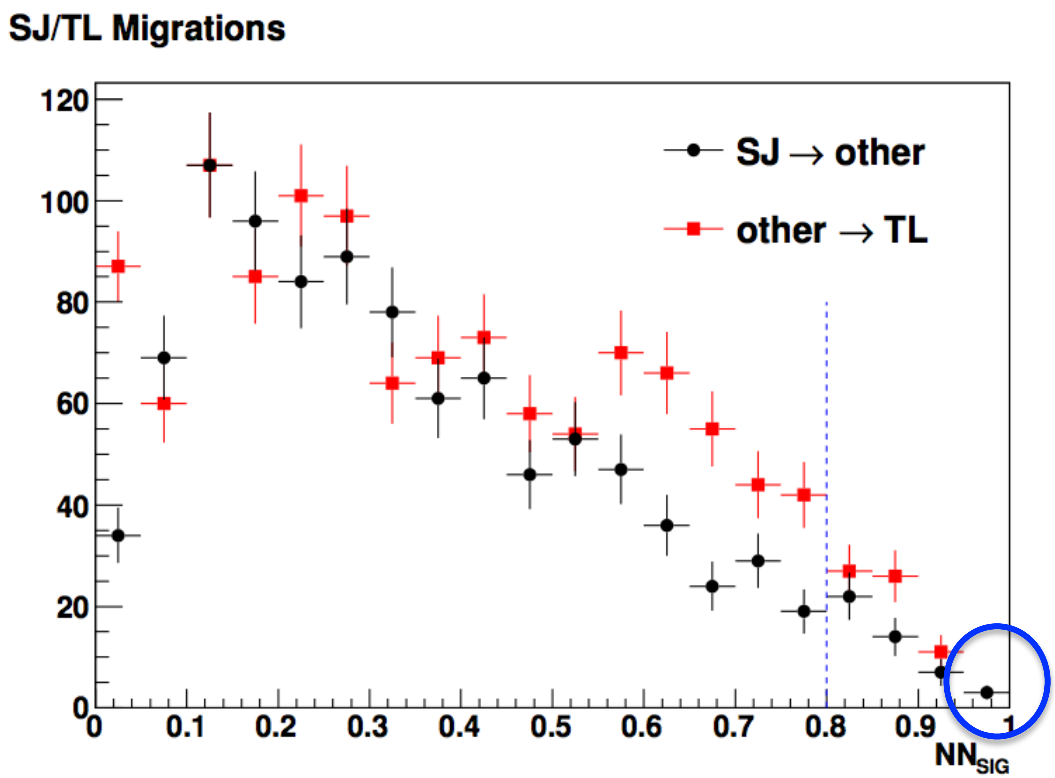
High Score: NN_{SIG} > 0.8 Observed Event Counts

Tag category	Background (fit)	Data
TT	39.5 ± 4.6	33
SS	37.6 ± 4.6	37
TL	67.4 ± 6.8	80
SJ	45.6 ± 5.1	62

Now: 6.5 events deficit at high score. Was: spot on

Excesses seen in both old and new tight-loose categories

Events Gained and Lost: TL and SJ



The NN_{SIG} function is unchanged since Moriond 2012. Selected, tagged events receive the same NN_{SIG} scores they always did.

Top three NN_{SIG} score events in the SJ analysis are no longer selected.

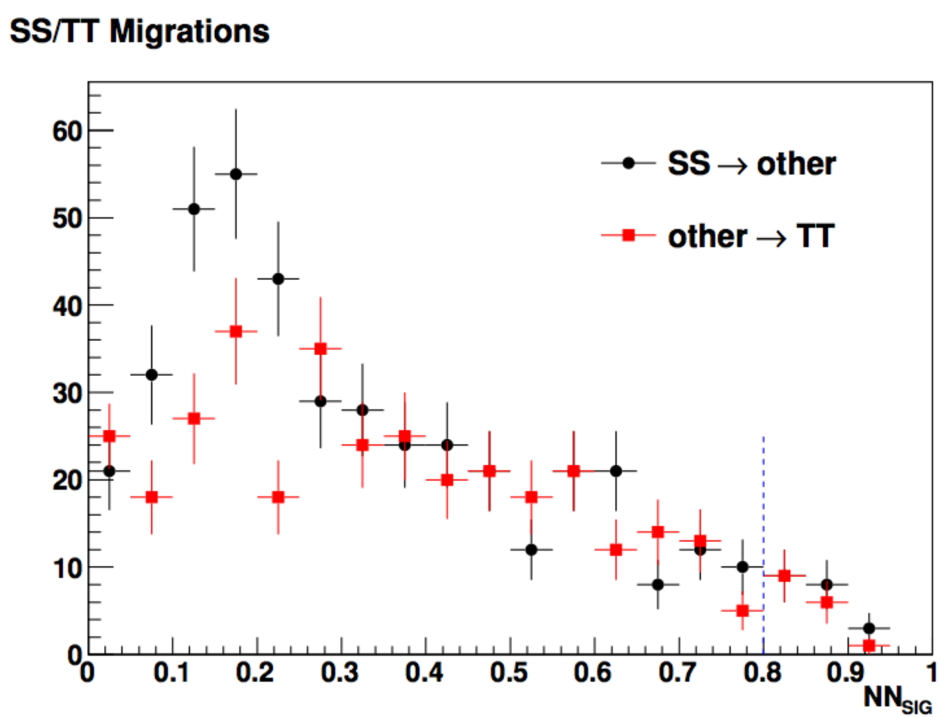
Two are now LL and one is 1L.

Bin has high s/b and a large weight in the result.

A test: We added these three events by hand to TL.

SECVTX+JP(redo) vs. HOBIT limit discrepancy changes from 47% to 31% with the events added back.

Events Gained and Lost: TT and SS



Lost More Events than Gained in the high-NN_{SIG} region.

Studied adding 5 extra candidates to the TT data by hand, following the background shape (not just the last bin).

Change in limit discrepancy: from 47% to 33%

Combined effect of TT and TL candidates: reduces discrepancy from **47% to 19%**

Improvement in sensitivity is 8% at m_H=125 GeV

How Likely is it?

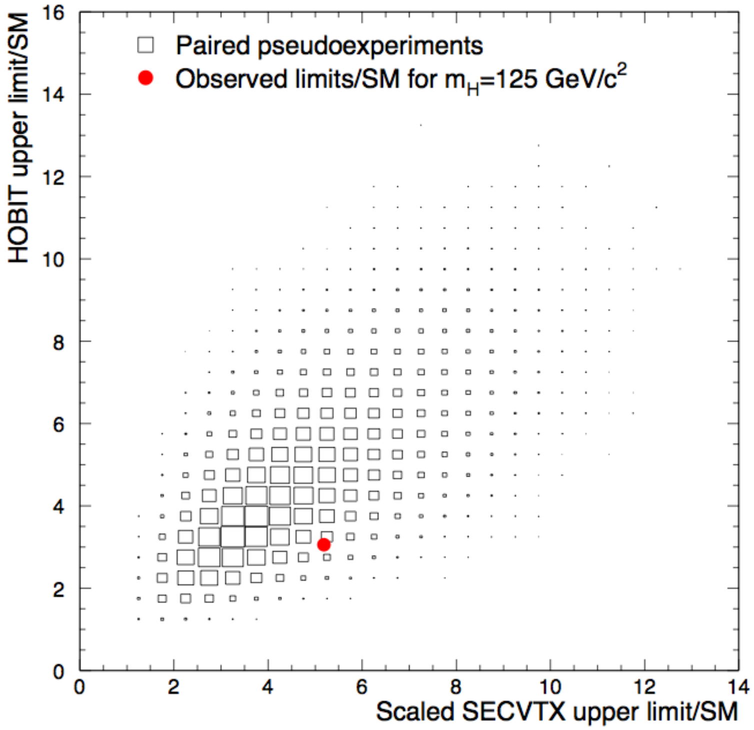
Compare CDF METbb HOBIT analysis with the re-done SECVTX+JP analysis

Paired pseudoexperiments:

- HOBIT channels TT, TL, 1T
- SECVTX channels SS, SJ, 1S
- Use expected overlaps in the $NN_{SIG} < 0.8$ and $NN_{SIG} > 0.8$ regions to generate independent samples of events in 15 categories:

TTSS, TTSJ, TT1S, TTnone
TLSS, TLSJ, TL1S, TLnone
1TSS, 1TSJ, 1T1S, 1Tnone
noneSS, noneSJ, none1S

Calculate limit for each pair of pseudoexperiments & compare

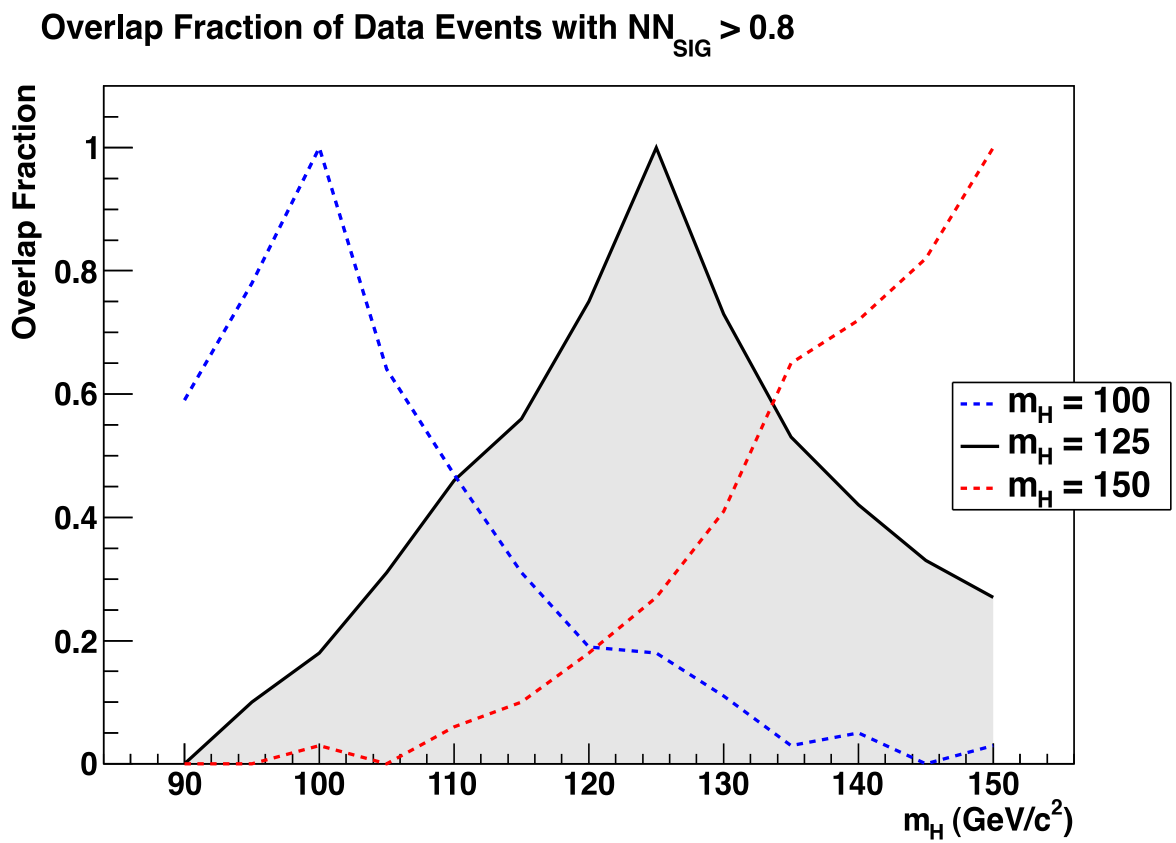


P-value for |Limit difference| to be as big as observed: 7%
Highly correlated over m_H range:
P-value for all limits to be low: 3-5%

How Correlated are the Searches at Each m_H?

Limited resolution on input variables to NN_{SIG} correlates results of searches at nearby masses.

Between 2 and 3 independent search results over the mass range $90 < m_H < 150$ GeV/c^2

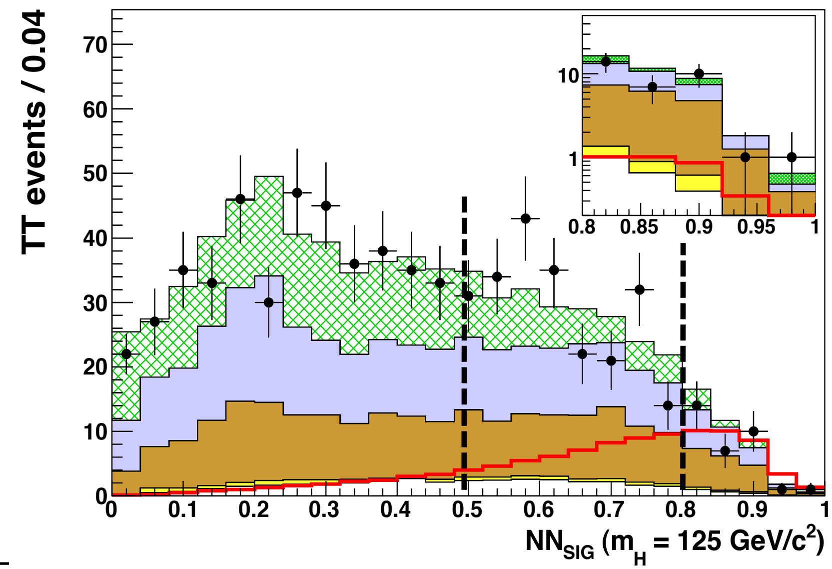


Studying Backgrounds in the Intermediate NN_{SIG} Score Region

Intermediate Score: $0.48 < NN_{SIG} < 0.8$

Background fits dominated by events at even lower NN_{SIG} score

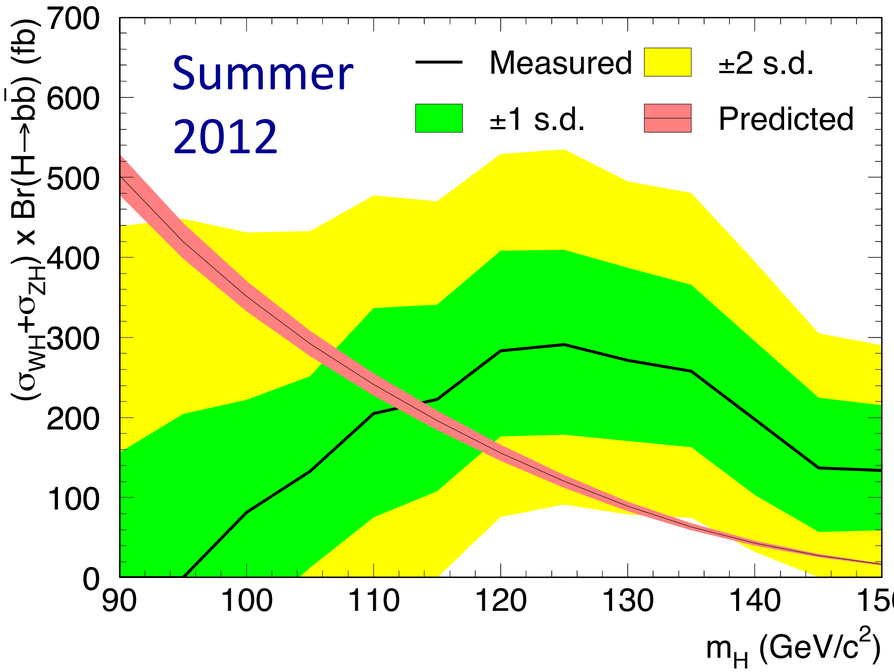
Limits on Higgs boson signal fairly insensitive to these bins.



Tag category	Background (fit)	Data
TT	264.8 ± 25.1	265
SS	228.8 ± 21.0	217
TL	506.1 ± 38.8	506
SJ	312.5 ± 22.6	291

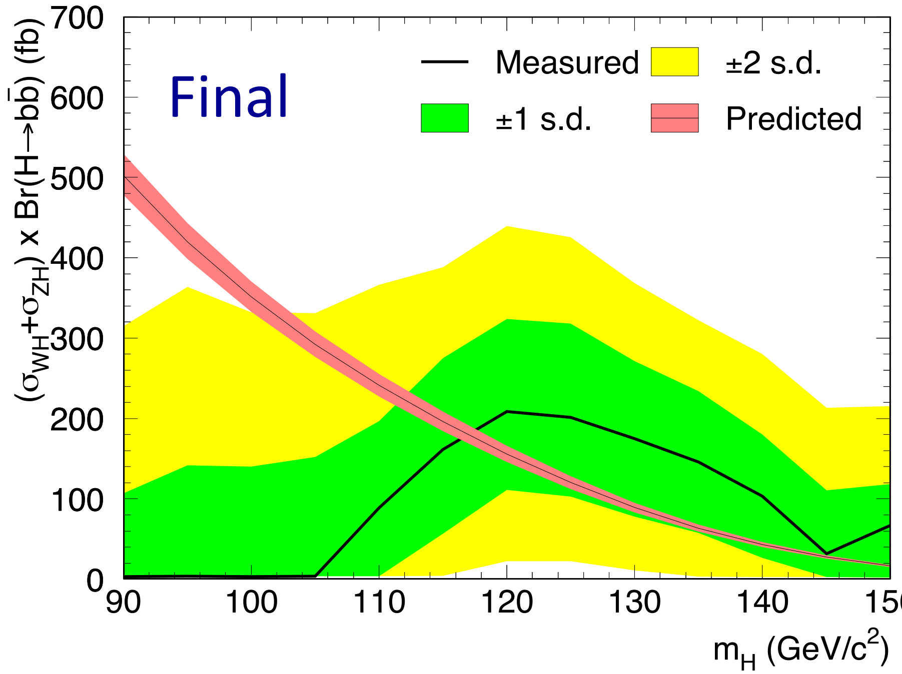
No evidence for mismodeling in this region

Final CDF Combined VH→Vbb Cross Section Measurements



At m_H=125 GeV/c^2 the previous measuement is

$$\sigma(WH+ZH)\times Br(H\to b\bar{b}) = 291^{+118}_{-113}\ \text{fb}$$



At m_H=125 GeV/c^2, the final measurement is

$$\sigma(WH+ZH)\times Br(H\to b\bar{b}) = 206^{+110}_{-104}\ \text{fb}$$

The SM prediction is

$$\sigma(WH+ZH)\times Br(H\to b\bar{b}) = 120 \pm 8\ \text{fb}$$

Summary of the H→bb Updates and Investigations

- Previous METbb (SECVTX+JetProb) analysis is still valid
  - Analysis redone with new framework, cuts, and systematic uncertainty handling
  - Previous METbb result reproduced with small shifts in limits
  - No change in combined limits or p-values
- Switching to a new b-tagger reclassified events – only 50% overlap with events in the old analysis in the highest-weight region.
- New best-fit cross sections are lower.
- We must choose the more sensitive analysis:
  HOBIT METbb is 8% more sensitive than the previous version at m_H=125 GeV/c^2, and 14% stronger on average in 90 < m_H < 150 GeV

Combining the SECVTX+JetProb Analysis and HOBIT Analysis?

Reasons to do it:

- More statistical power
- Observed results may be intermediate between published and new results

Reasons not to do it:

- Expected sensitivity gain is very small – signal events are expected to remain tagged, merely shuffled from one category to another
- More exclusive tag categories (15 instead of 3). Smaller data control samples mean higher systematic uncertainties
- HOBIT uses SECVTX variables as inputs, among others. It's already a combination.
- Combining HOBIT and SECVTX+JetProb was not on our original menu of analysis improvements, for the above reasons. We made the decision to switch all analyses from SECVTX+JetProb to HOBIT without knowledge of the data outcome. Switching *a posteriori* would bias the final result.

Predicted Event Overlap Fractions, signal MC

	0T		1T		TL		TT	
0S			—	22%	—	19%	—	6%
1S	*17%*	—	*63%*	67%	*15%*	31%	*6%*	11%
SJ	*12%*	—	*20%*	9%	*37%*	35%	*32%*	23%
SS	*5%*	—	*3%*	1%	*15%*	15%	*77%*	61%

Roman font – normalized to HOBIT yields. Italics: Normalized to SECVTX+JP yields

Updates Since the last full CDF SM Higgs Combination

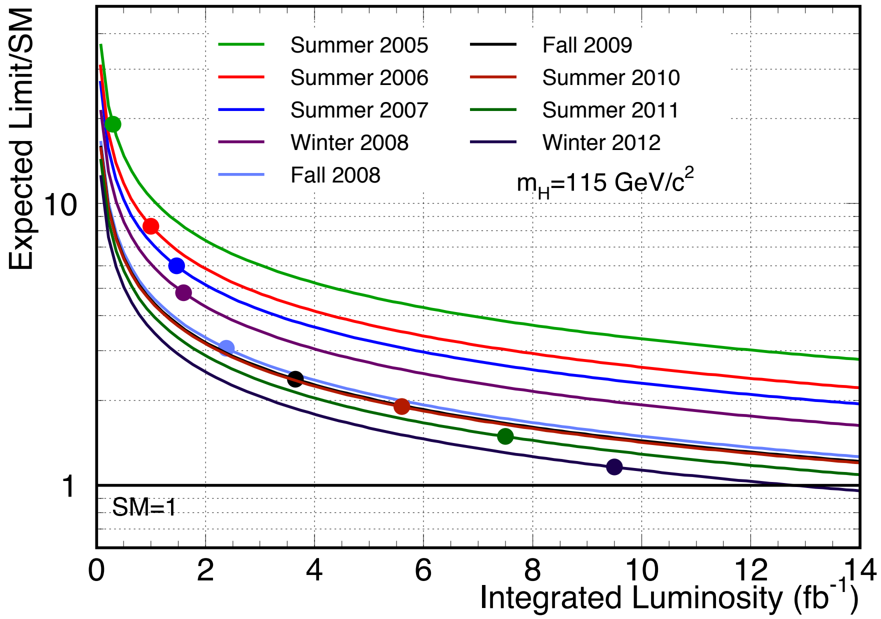
- Revert to the published 6.0 fb^{-1} $H \rightarrow \tau\tau$ Search.
  8.3 fb^{-1} preliminary result not published.
- Update the $t\bar{t}H$ search: train MVA's at each m_H.
- Improve correlations/anticorrelations in b-tag uncertainties in llbb / lvbb analyses
- Upgraded the Central-Central $H \rightarrow \gamma\gamma$ search to use an MVA instead of $m_{\gamma\gamma}$.
  Searches including plug photons and conversions still use $m_{\gamma\gamma}$.

CDF's SM combination last done for Winter 2012 conferences.

All CDF SM Search Channels

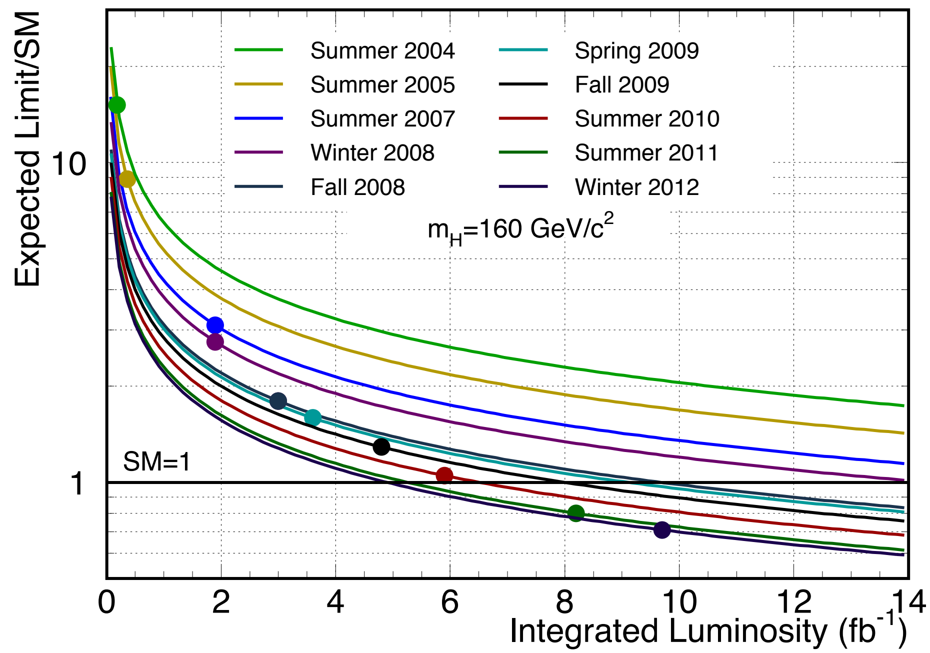
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)	9.45	90-150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)	9.45	90-150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)	9.45	90-150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	9.45	90-150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(4 b-tag categories)	9.45	90-150
$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(2 or more 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)	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)+(tri-leptons with 2 or more jets)	9.7	110-200
$H \to ZZ$ (four leptons)	9.7	120-300
$H \to \tau^+\tau^-$ (1 jet)+(2 or more jets)	6.0	100-150
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)	9.45	100-150
$H \to \gamma\gamma$ 1×(0 jet)+1×(1 or more jets)+3×(all jets)	10.0	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (4 jet, 5 jet, $\geq$ 6 jet)×(5 b-tag categories)	9.45	100-150

Sensitivity Evolution over Time

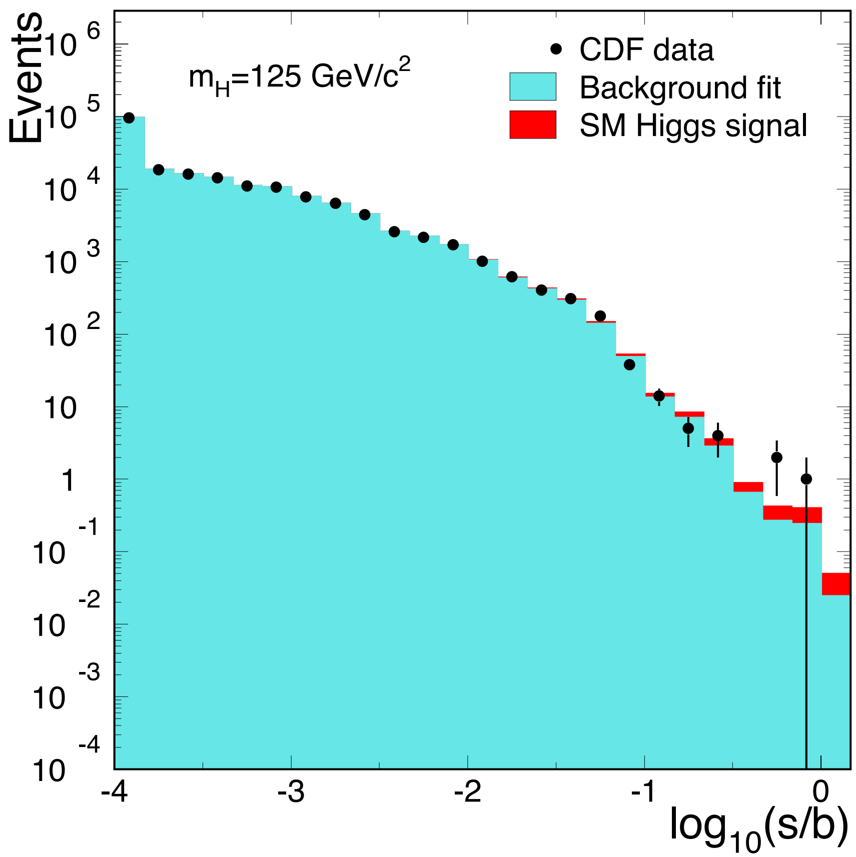


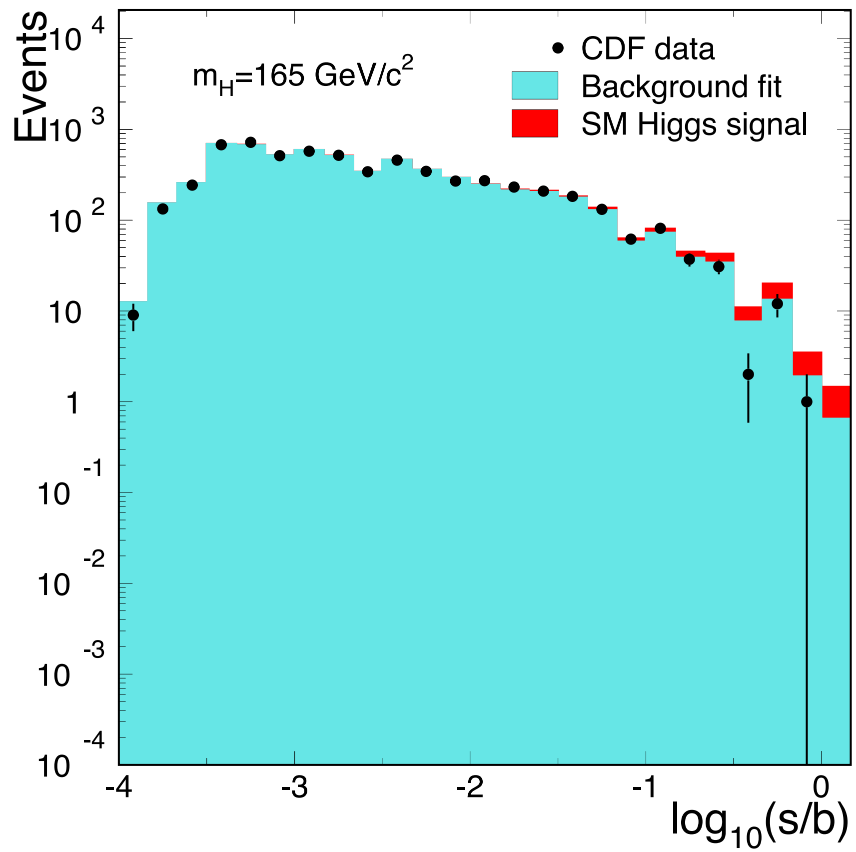
We collected data, and we also learned how to get more out of the data.

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



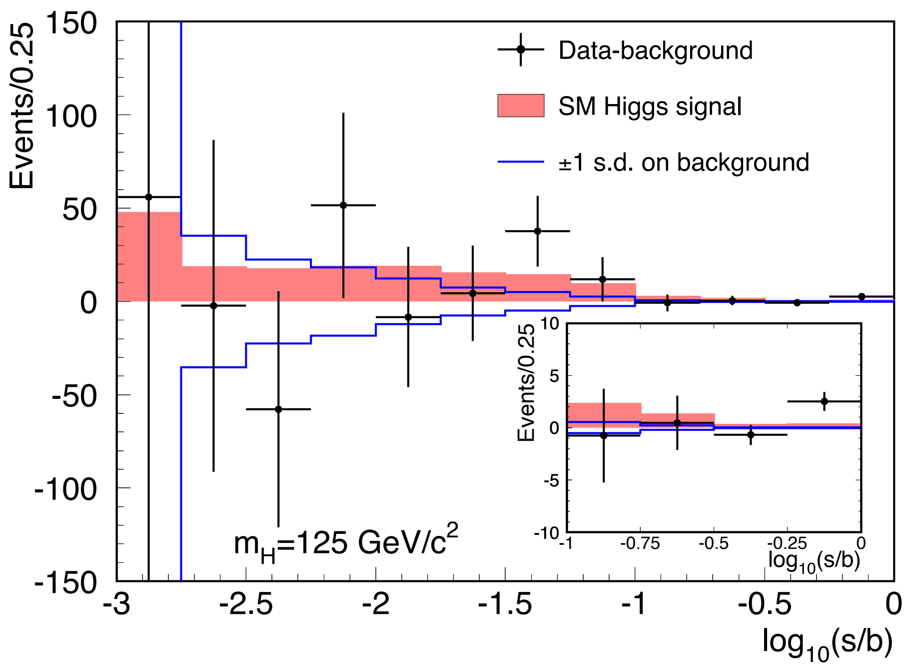
SM Combined Data Summaries at m_H=125 and 165 GeV/c^2

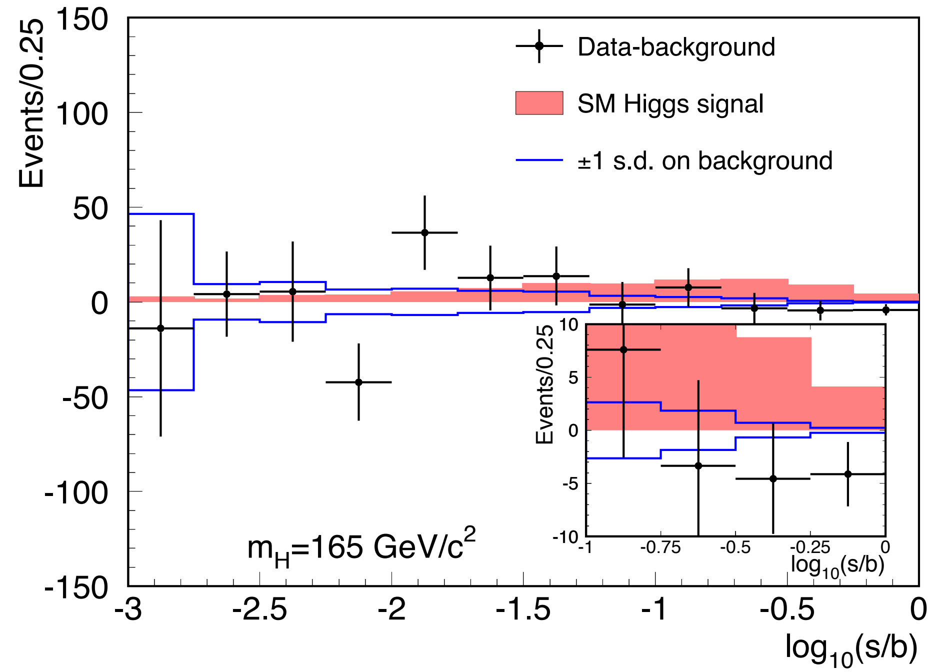




Background Hypothesis fit to data
Bins of similar s/b added together

SM Combined Data Summaries at m_H=125 and 165 GeV/c^2

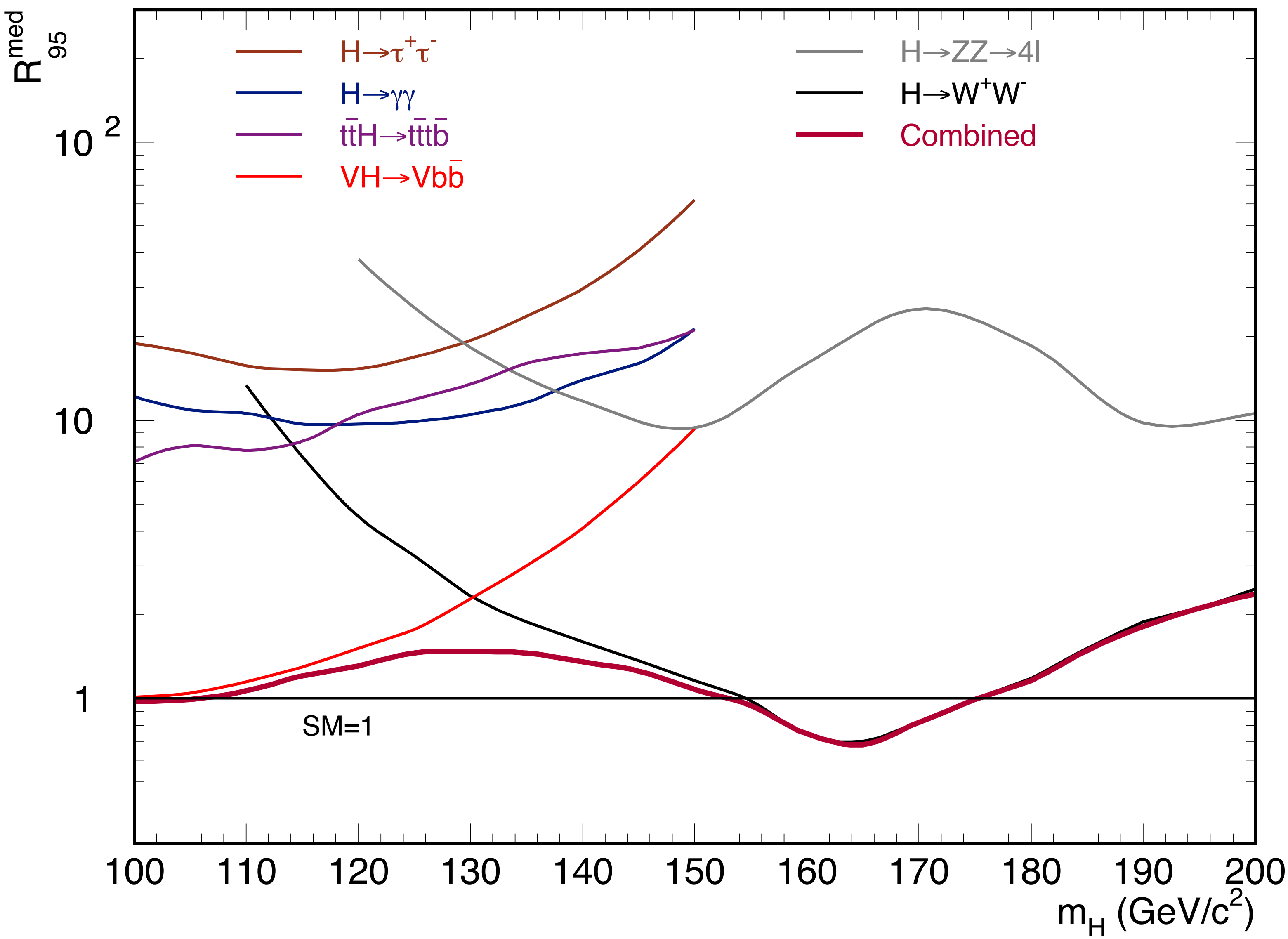




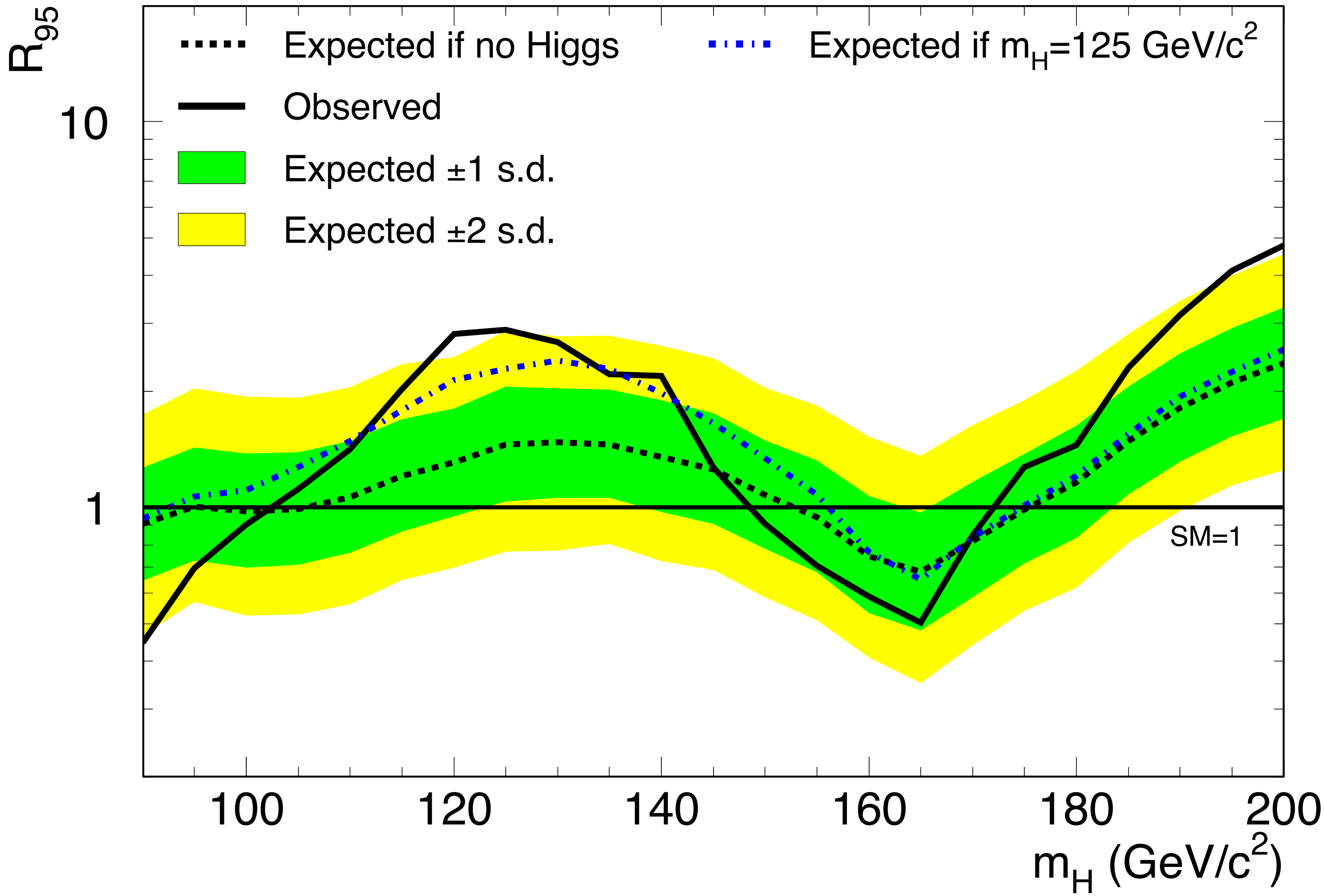
Same as before, but fitted background subtracted from the data.

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

Sensitivity of the Main Search Channels

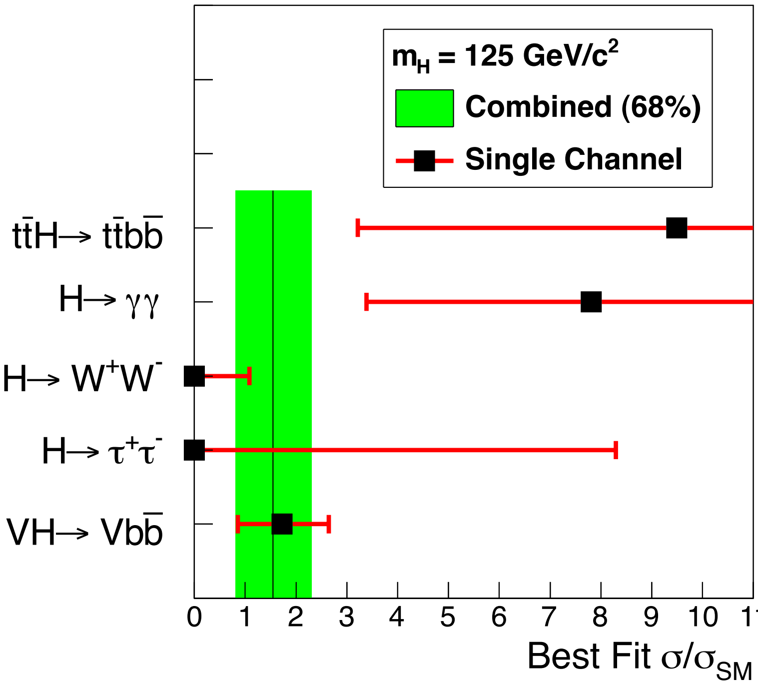


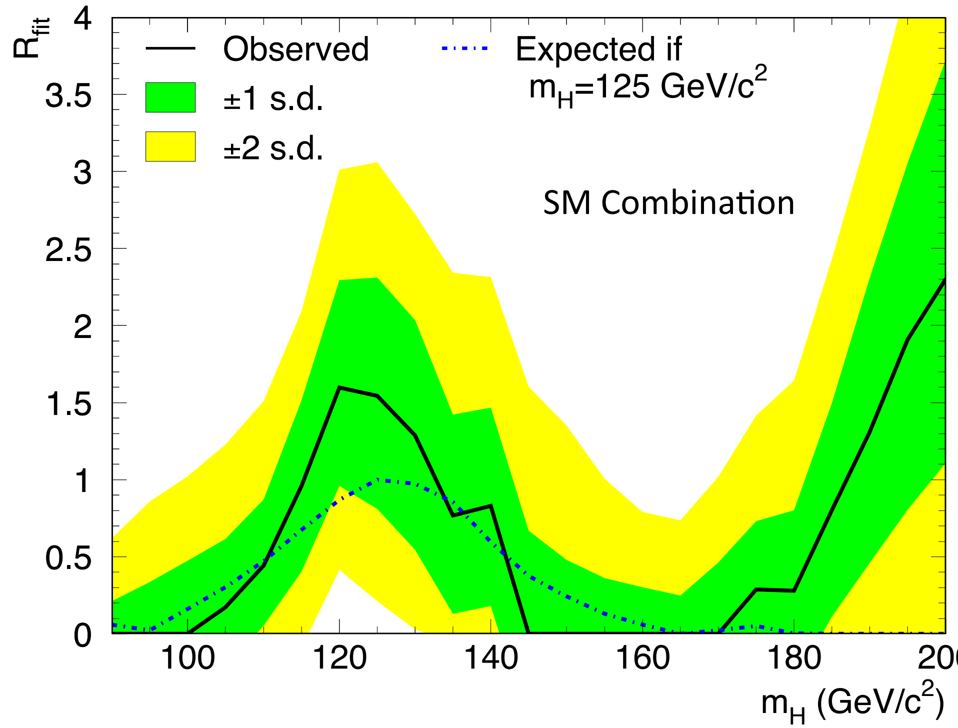
CDF's Final SM Higgs Rate Limits



Excluded regions: $90 < m_H < 102$ GeV/c^2 and $149 < m_H < 172$ GeV/c^2
Expect to exclude if no Higgs: $90 < m_H < 94$ GeV/c^2, $96 < m_H < 106$ GeV/c^2, and $153 < m_H < 175$ GeV/c^2

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





$$t\bar{t}H \rightarrow t\bar{t}b\bar{b}: \quad 9.49^{+6.60}_{-6.28} \times \mathrm{SM}$$

$$H \rightarrow \tau^+\tau^-: \quad 0.00^{+8.44}_{-0.00} \times \mathrm{SM}$$

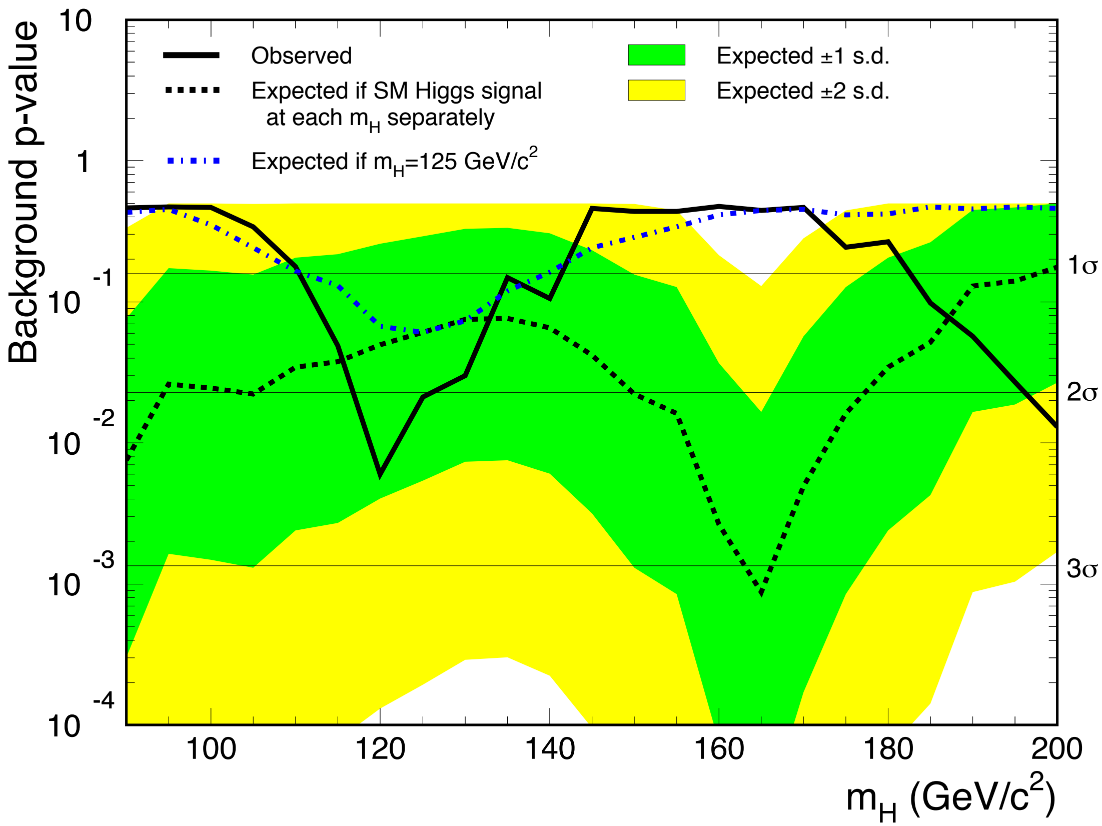
$$H \rightarrow \gamma\gamma: \quad 7.81^{+4.61}_{-4.42} \times \mathrm{SM}$$

$$VH \rightarrow Vb\bar{b}: \quad 1.72^{+0.92}_{-0.87} \times \mathrm{SM}$$

$$H \rightarrow W^+W^-: \quad 0.00^{+1.78}_{-0.00} \times \mathrm{SM}$$

$$\text{Combined}: \quad 1.54^{+0.77}_{-0.73} \times \mathrm{SM}$$

CDF's Combined SM Higgs Boson Search p-value



Observed local significance at m_H=125 GeV/c^2 is 2.0σ

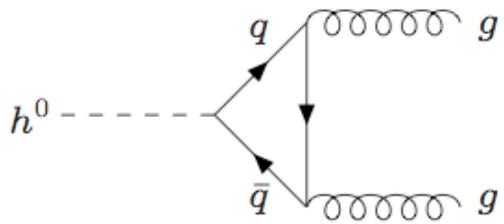
Expected significance at m_H=125 GeV/c^2 is 1.6σ assuming a signal is present.

2.5σ local significance at m_H=120 GeV/c^2

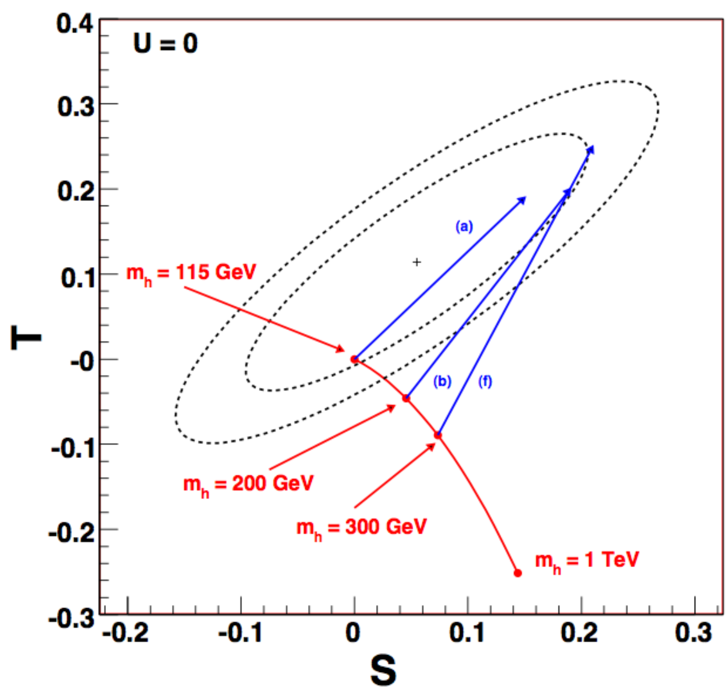
Look-Elsewhere Effect:

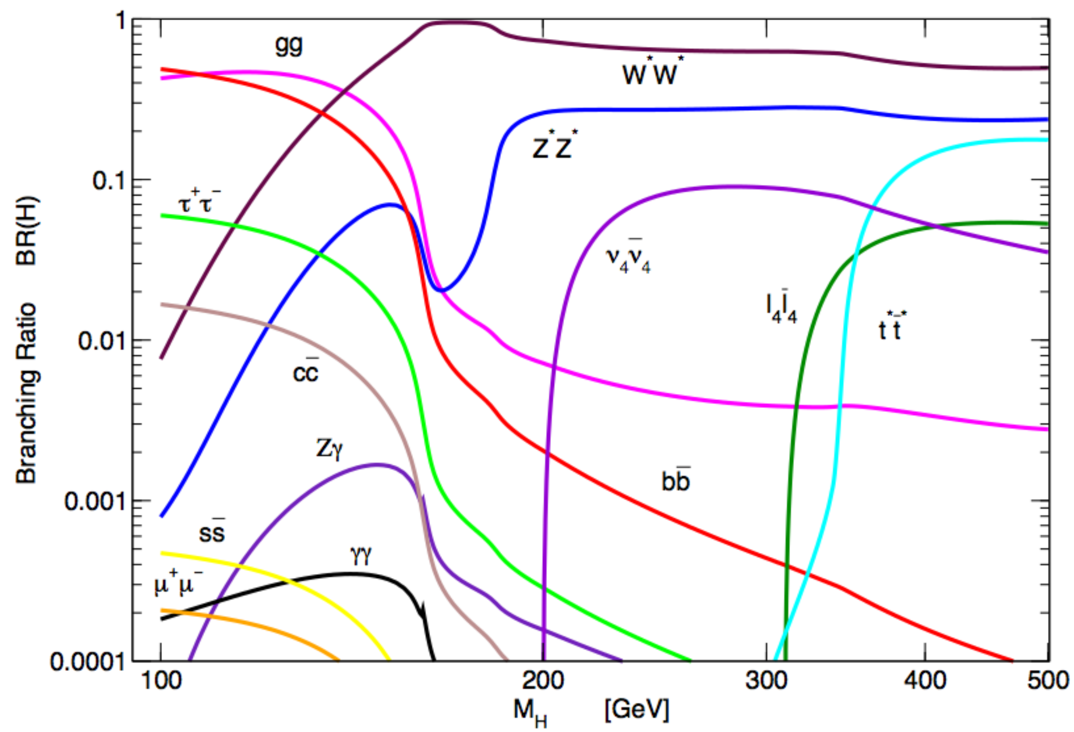
- m_H~125 GeV has been firmly established by the LHC
- CDF's mass resolution is not very sharp -- ~2 independent search results in H→bb, ~2 in H→WW
- Technical challenge – MVA's trained at each m_H separately. Histograms of predictions exchanged. Would need to exchange correlated pseudoexperiments to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

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



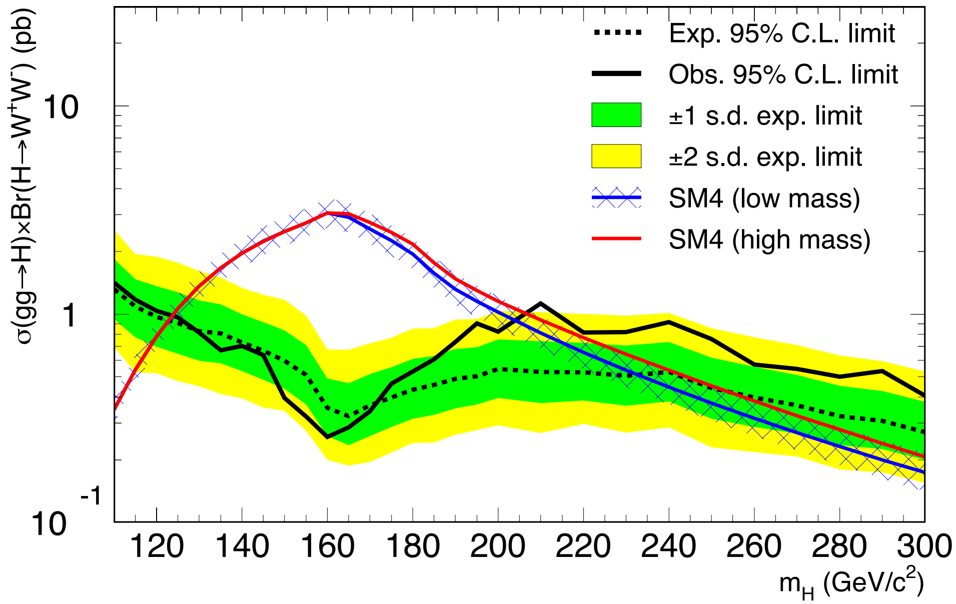
A heavy fourth generation of quarks would scale the gg→H production rate at colliders by a factor of ~9.
But watch out for H→$\nu_4\nu_4$ decays.
E. Arik et al., Acta Phys. Polon. B **37**, 2839 (hep-ph/0502050)





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

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

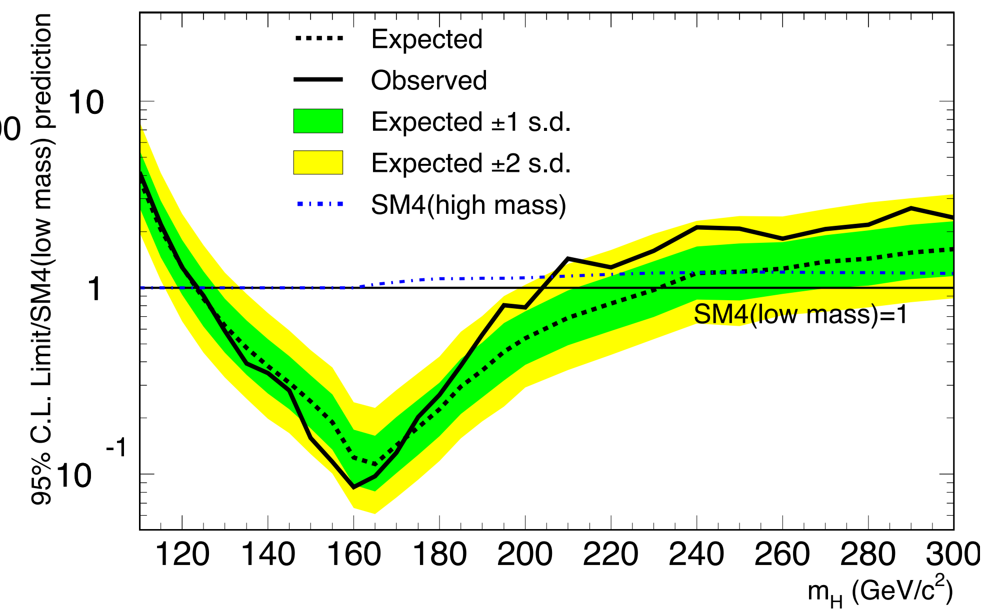


Searches optimized specifically for gg→H (NN's not trained with WH, ZH, or VBF).

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

Low-Mass scenario: m_{l4}=100 GeV, $m_{\nu 4}$=80 GeV
High-Mass scenario: m_{l4}=$m_{\nu 4}$=1 TeV
Both Scenarios: m_{d4}=400 GeV, m_{u4}=450 GeV

SM4 Cross Sections computed at NNLO in QCD by Anastasiou, Boughezal, and Furlan



Low-mass scenario exclusions:
Expected exclusion: 123 < m_H < 231 GeV/c^2
Observed exclusion: 124 < m_H < 203 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.

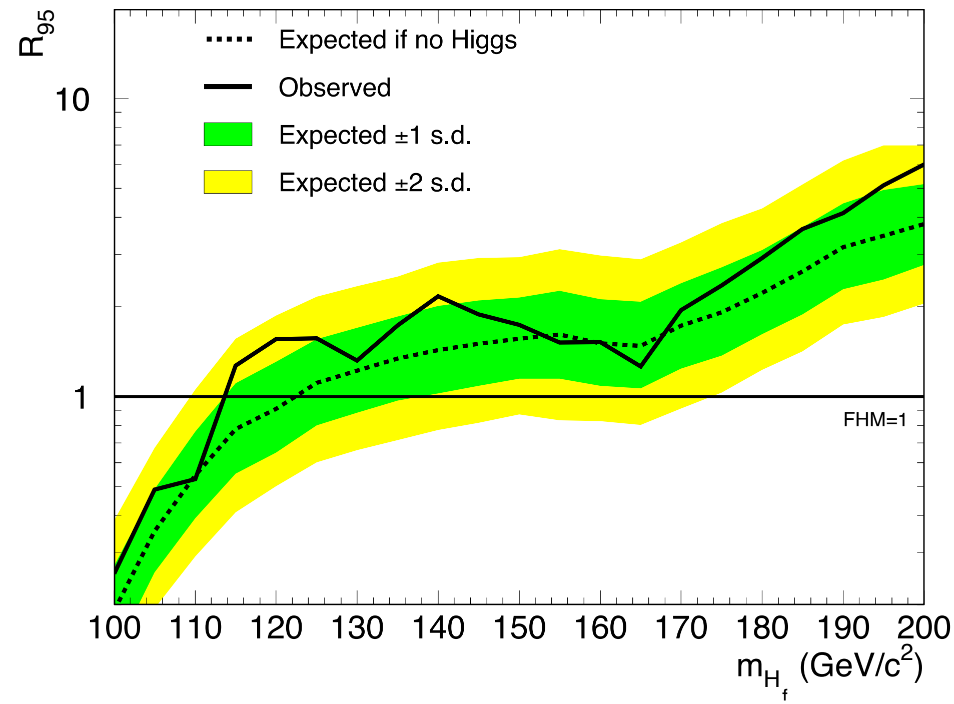
Included channels: H→γγ, H→WW, H→ZZ→4l

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: $100 < m_H < 113$ GeV/c^2
Expected exclsuion: $100 < m_H < 122$ 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 $\boldsymbol{\kappa_f}$

HWW coupling is scaled by $\boldsymbol{\kappa_W}$
HZZ coupling is scaled by $\boldsymbol{\kappa_Z}$

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

Standard Model is recovered if $\kappa_f = \kappa_W = \kappa_Z = 1$

Constraining Couplings

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

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

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

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

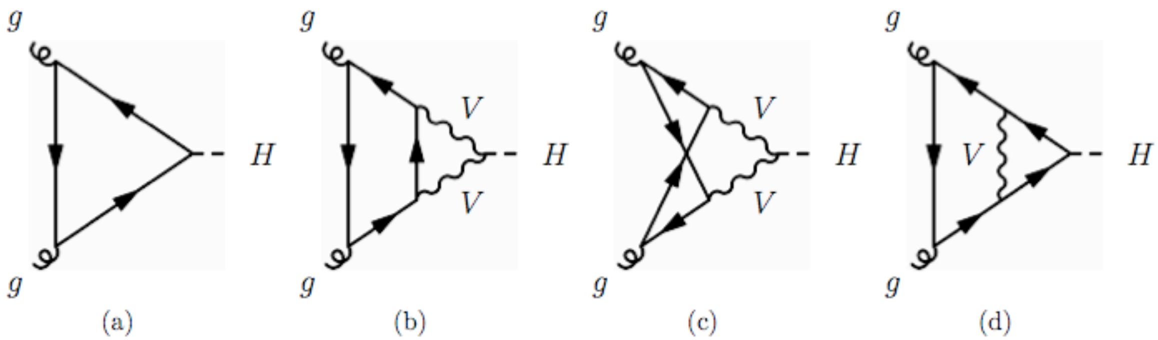
LO relations, but mostly true at higher order (most QCD affects the colored initial-state particles. There is gg→WH at higher order, however.)

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

-- Pretty much by definition! Unless NNLO VBF includes the EW ggH piece. From Bolzoni, Moch, Maltoni, and Zaro's papers, it seems as if the EW ggH piece is not in the NNLO VBF calculation.

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

Two-Loop Electroweak Contributions to the ggH Coupling

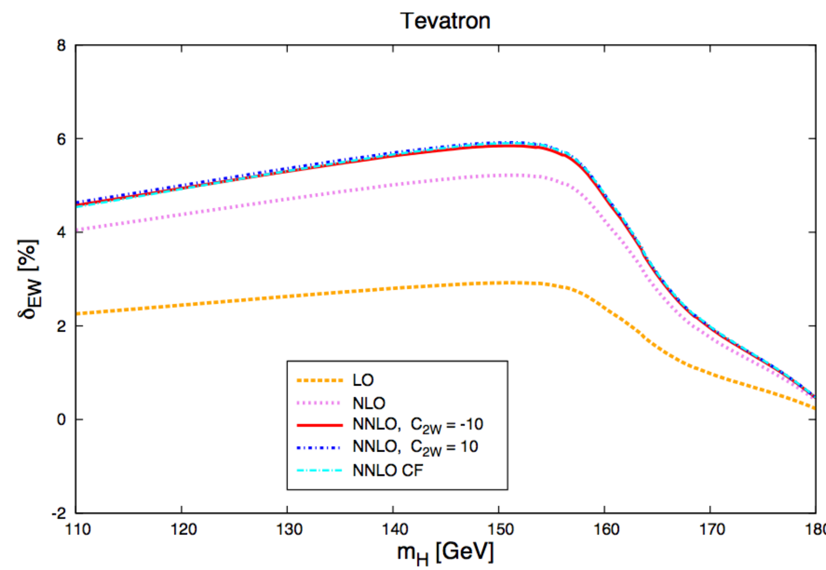


Aglietti, Bonciani, Degrassi and Vicini,
arXiv:hep-ph/0610033

Anastasiou, Boughezal, Petriello,
JHEP 0904 003 (2009)

Actis, Passarino, Sturm, Uccirati
PLB 670, 12 (2008)

Grazzini and de Florian
PLB 674, 291 (2009)



- Approximately a 5% contribution to the gg→H production cross section at m_H=125 GeV/c^2. Main contribution is from interference with the LO process.
- Contribution not included in VBF calculation (HAWK: Denner, Dittmaier, Mück)

Constraining Couplings

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

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

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

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

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

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

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

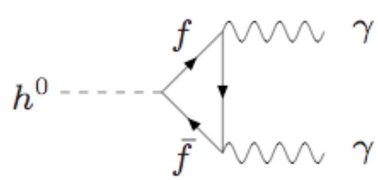
$$\Gamma(H \to \gamma\gamma) = \Gamma_{SM}(H \to \gamma\gamma)\left|\alpha\kappa_V + \beta\kappa_f\right|^2$$

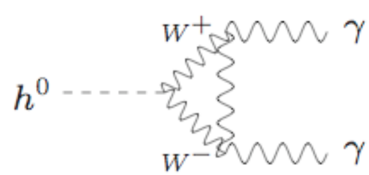
Other modes, like $H \to \mu^+\mu^-$ and $H \to Z\gamma$ have very small widths

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

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

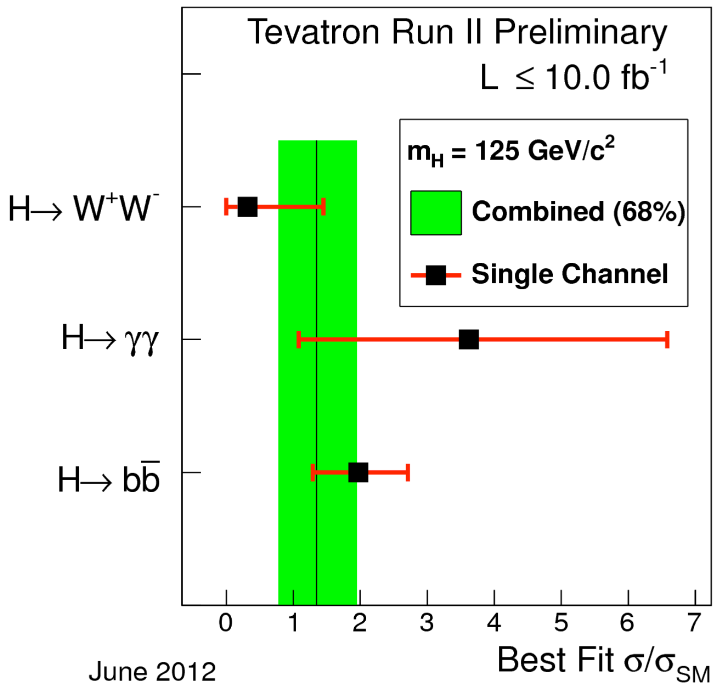
$\alpha = 1.28 \quad \beta = -0.21$

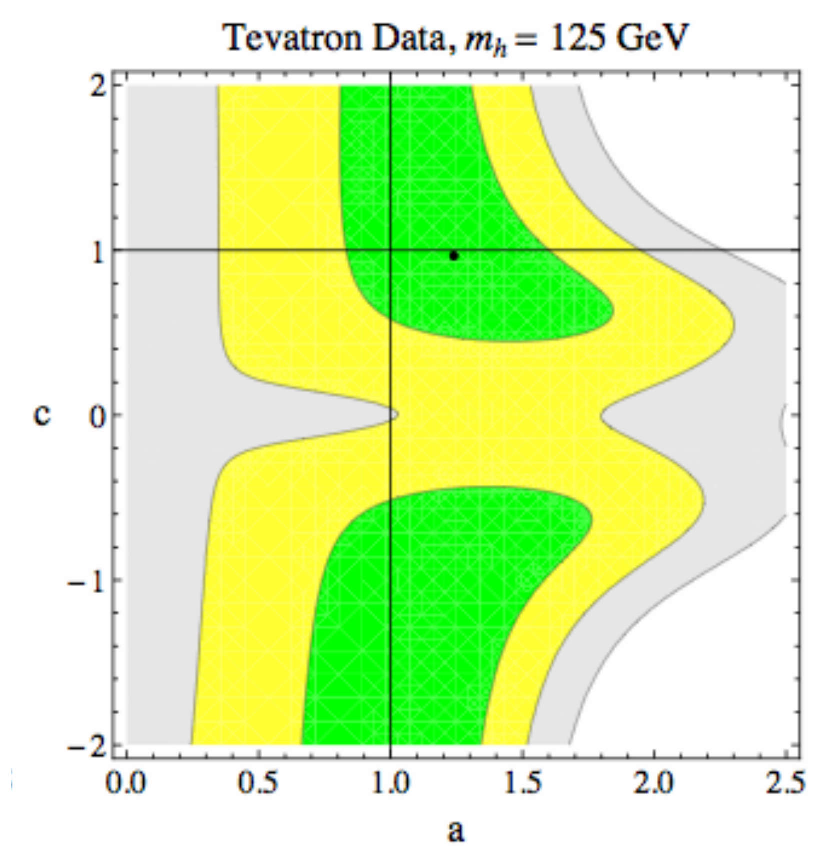




Some work from theorists

Espinosa, Grojean, Mühlleitner, and Trott, “First Glimpse at Higgs’ Face”, arXiv:1207.1717v2 (updated Aug. 21 with post-ICHEP data) JHEP 1212, 045 (2012).





$a=\kappa_V$, $c=\kappa_F$

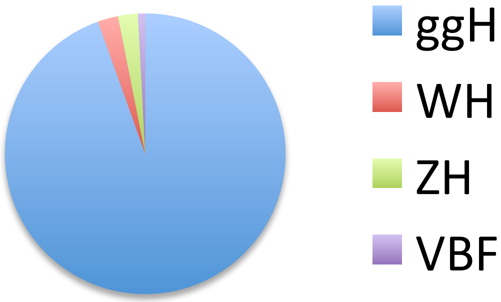
More Complete Treatment of Signal Scalings

Example: HWW Search. All Signals have H→WW, but different mixtures of production mechanisms in each search channel.

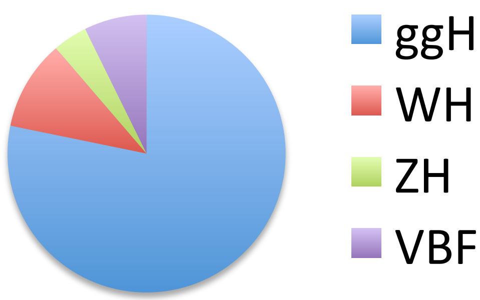
Each signal contribution should be scaled by the appropriate factor

Pie charts show relative contributions.

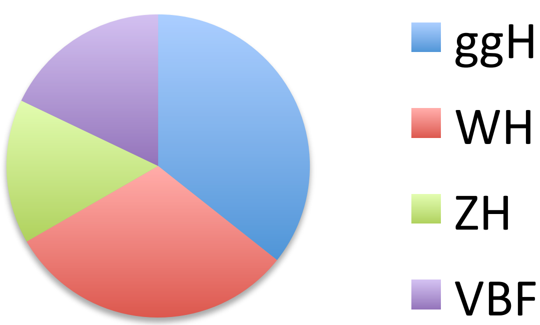
Zero Jets



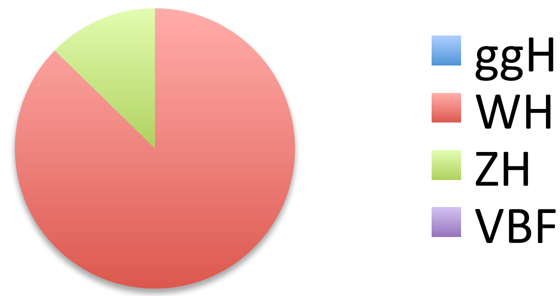
One Jet



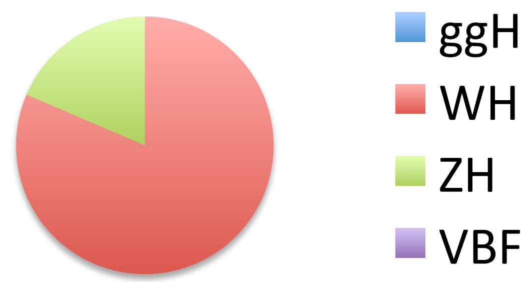
Two or More Jets



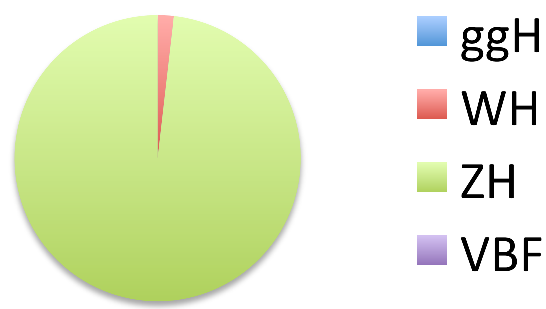
Same Sign di-leptons



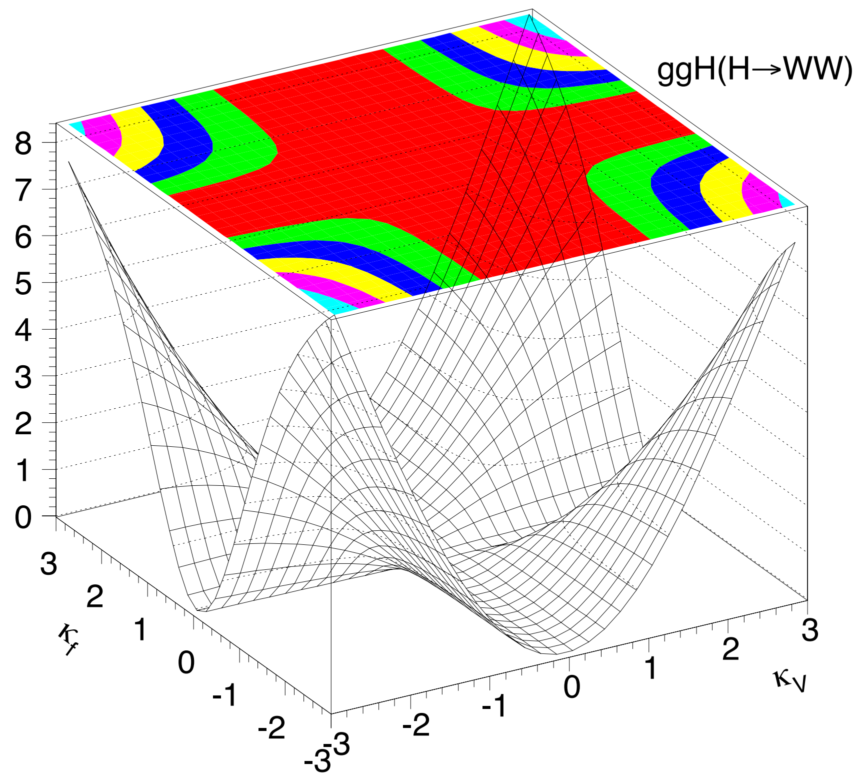
Tri-Leptons Z-rejected

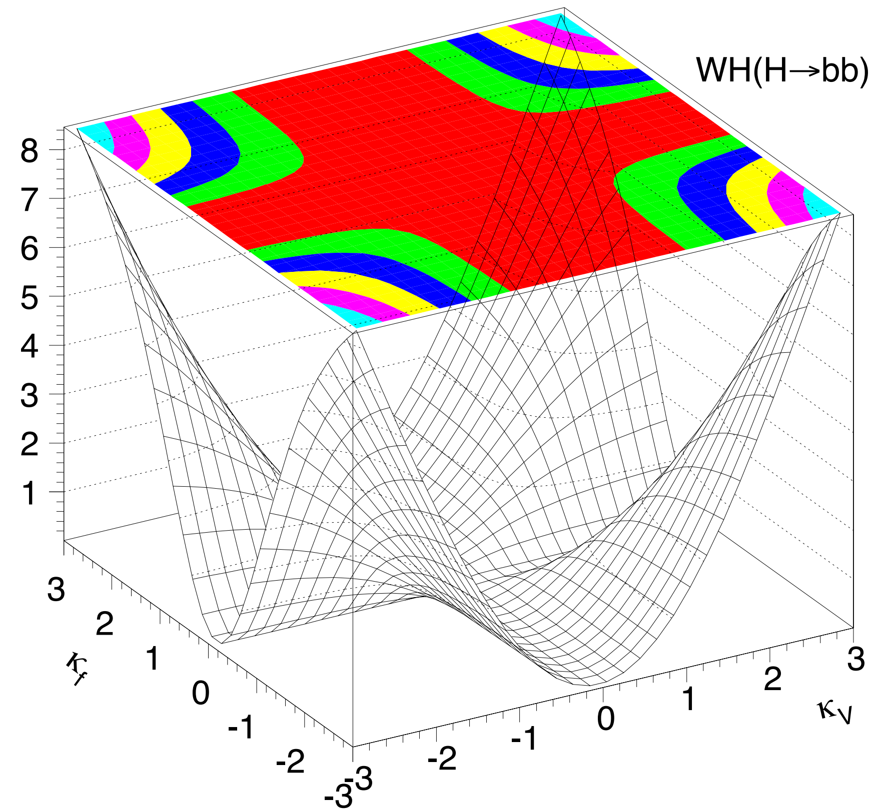


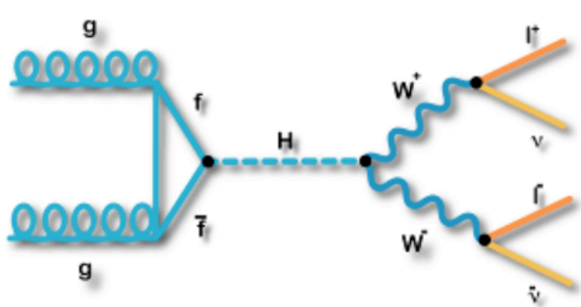
Tri-Leptons Z-selected

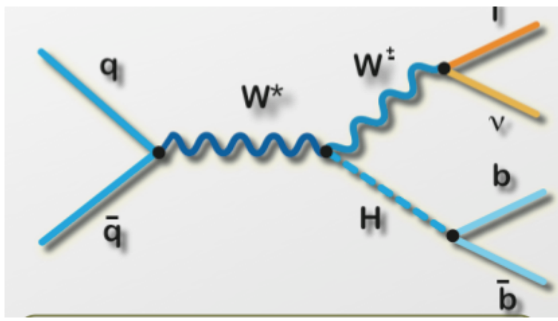


Signal Rate Enhancement Factors for gg→H→WW and WH->lvbb

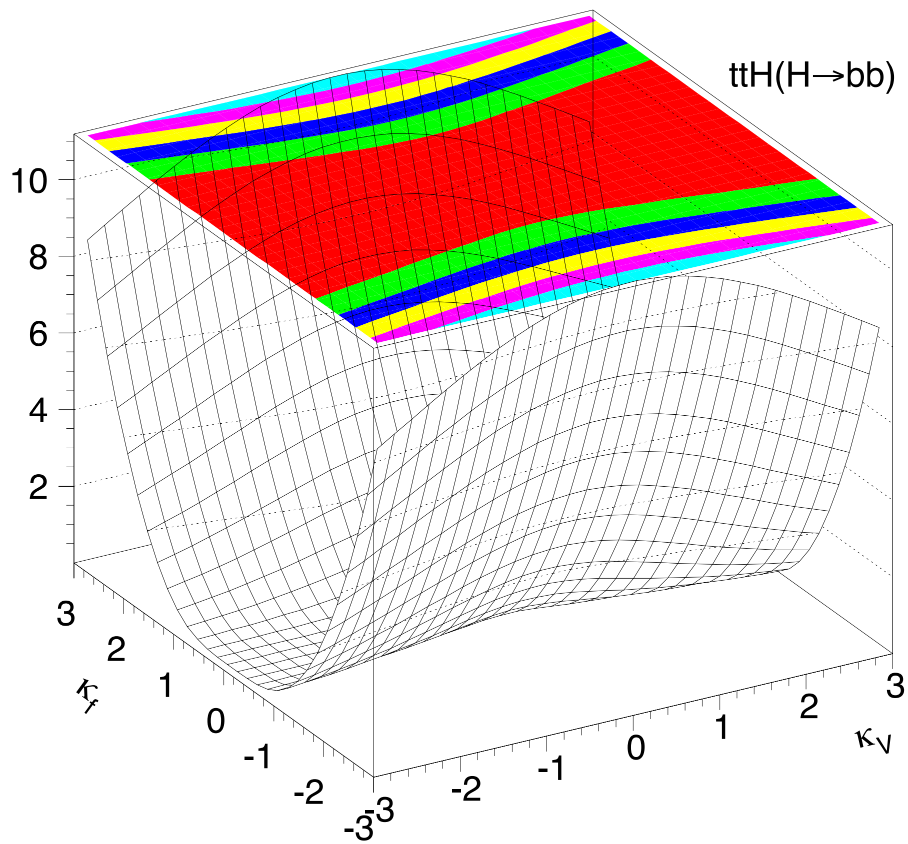


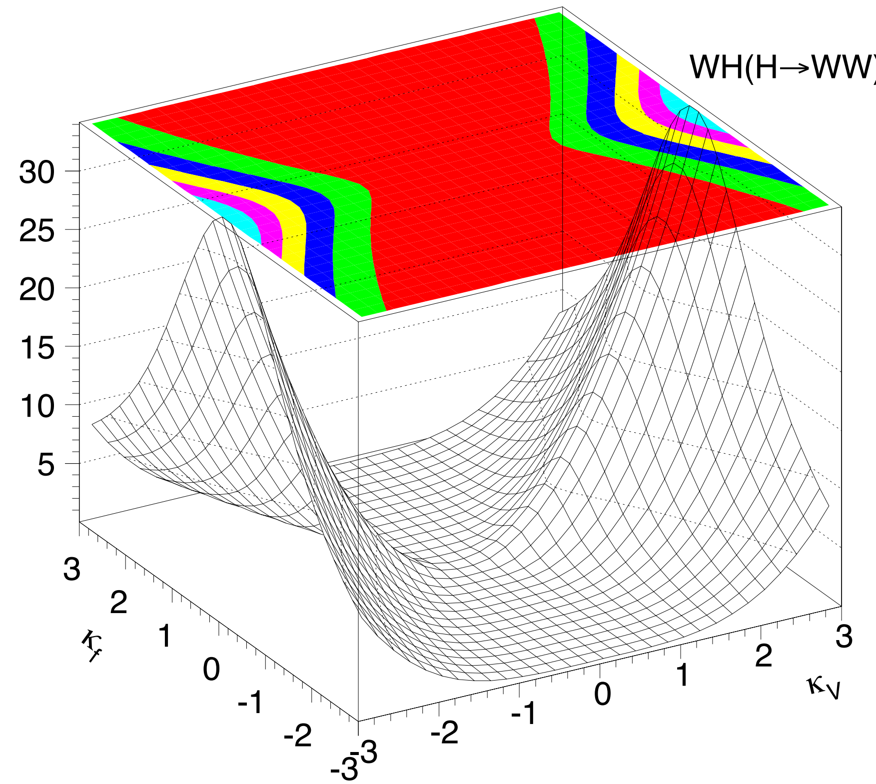


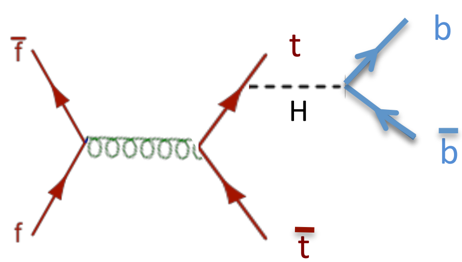


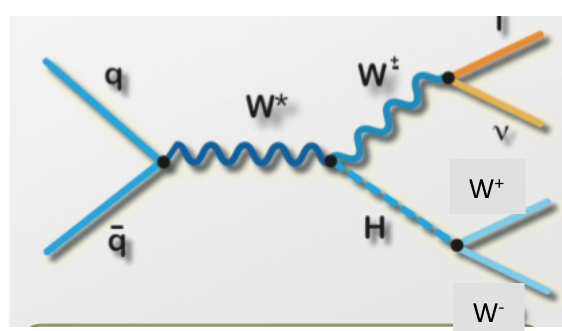


Signal Rate Enhancement Factors for ttH→ttbb and WH->WWW

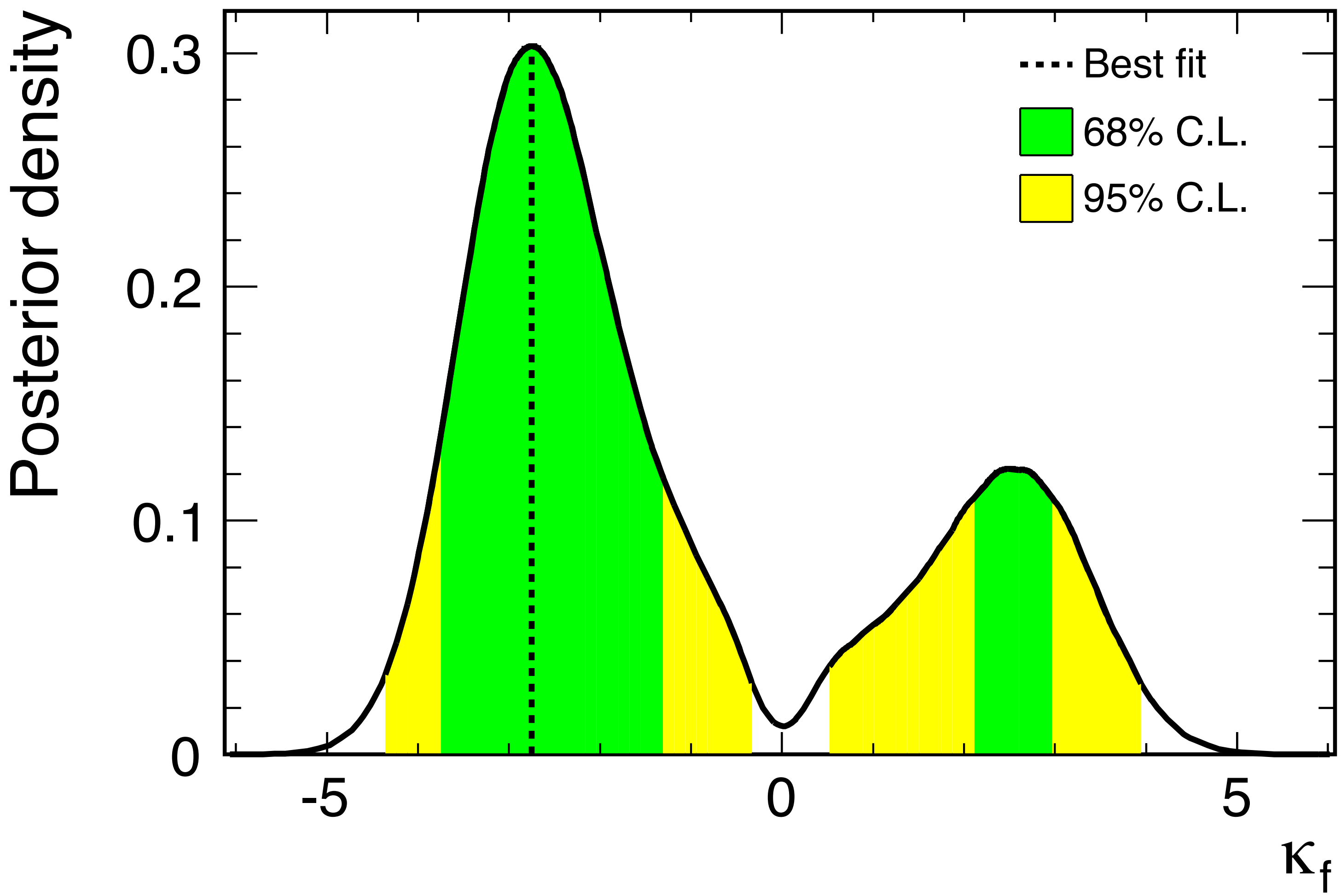








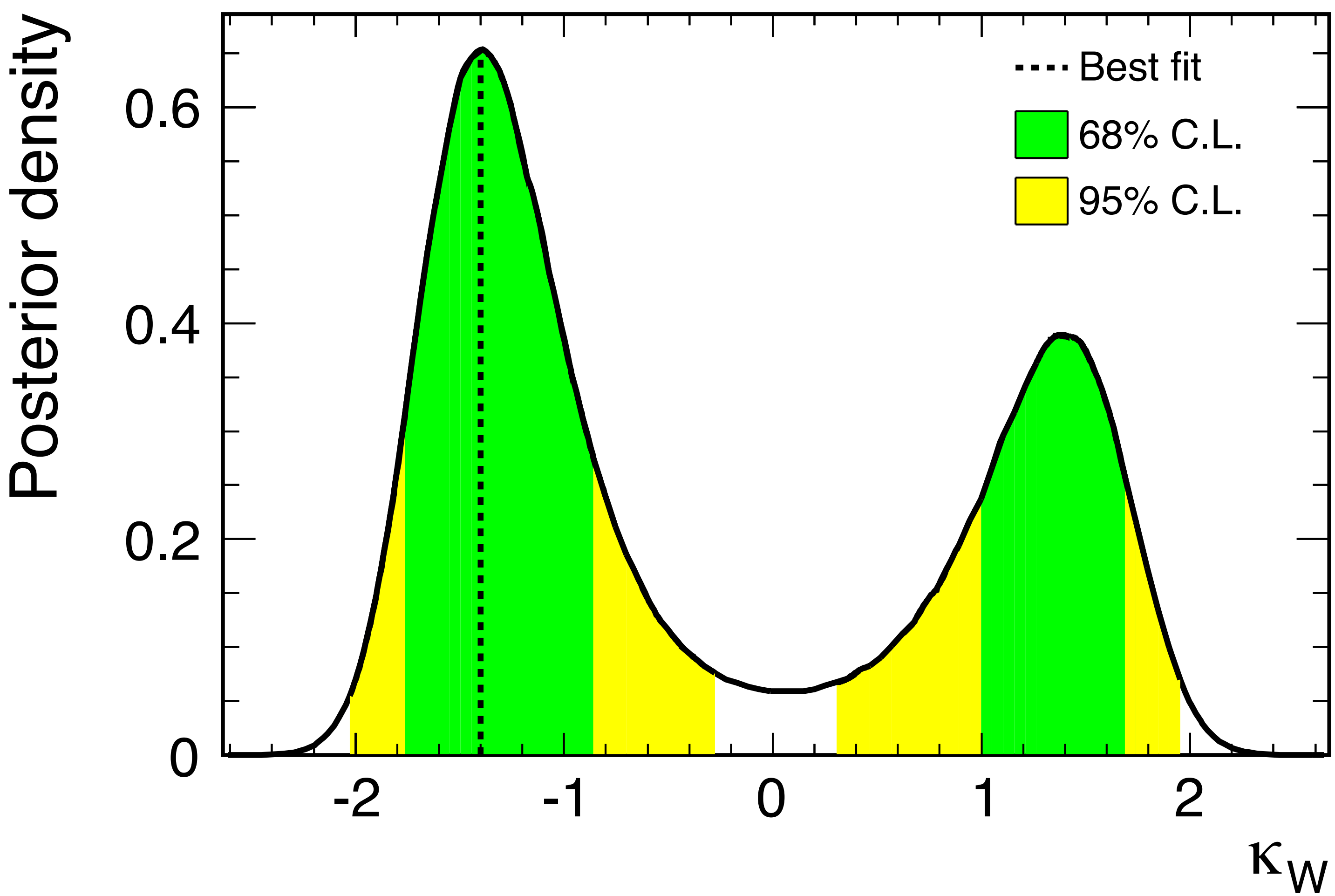
Posterior Constraint on the Hff Coupling Factor κ_f



- Uniform prior assumed
- $\kappa_W = \kappa_Z = 1$ assumed

Excess in the $H \rightarrow \gamma\gamma$ searches drives the asymmetry from positive and negative coupling scale factors

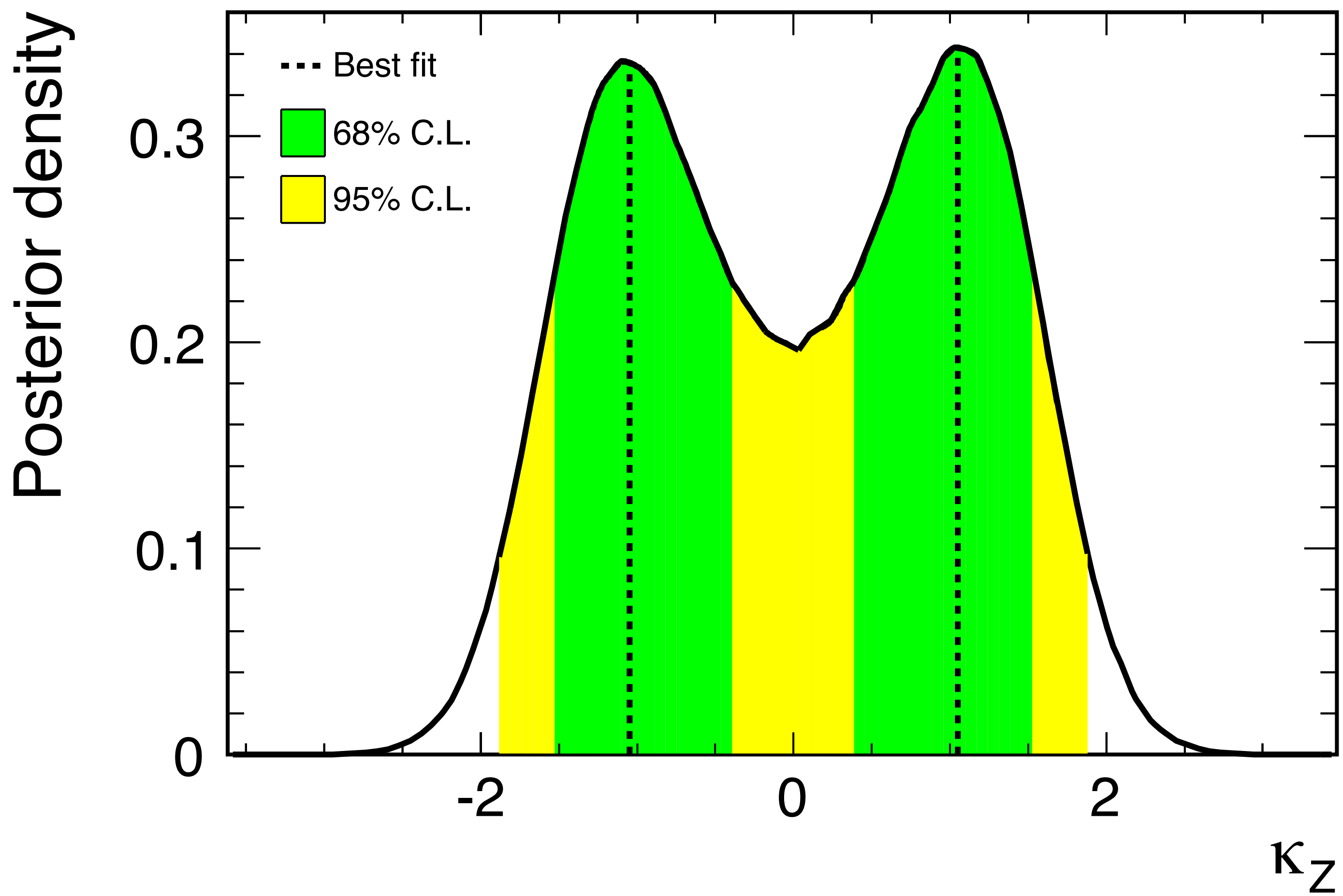
Posterior Constraint on the HWW Coupling Factor κ_W



- Uniform prior assumed
- $\kappa_f = \kappa_Z = 1$ assumed

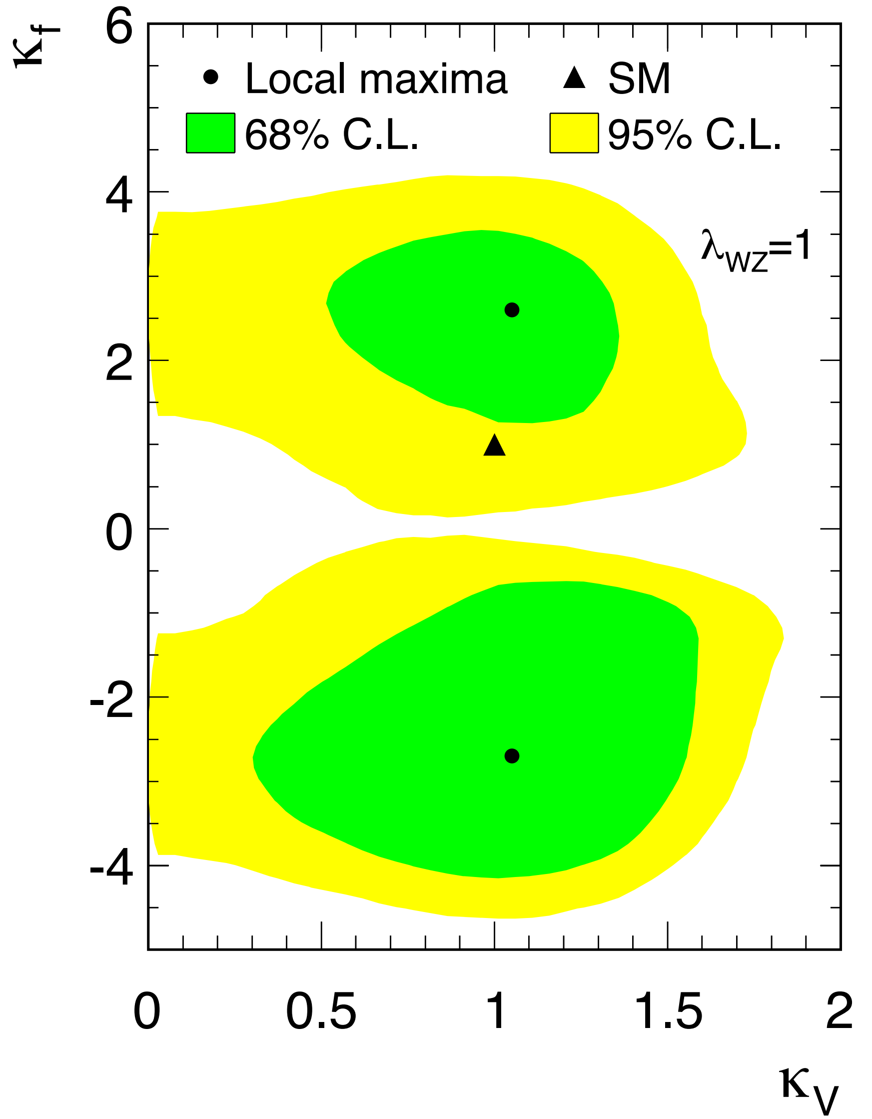
Excess in the $H \rightarrow \gamma\gamma$ searches drives the asymmetry from positive and negative coupling scale factors

Posterior Constraint on the HWW Coupling Factor κ_Z



- Uniform prior assumed
- $\kappa_f = \kappa_W = 1$ assumed

Two-Dimensional Constraints: Bosons vs. Fermions

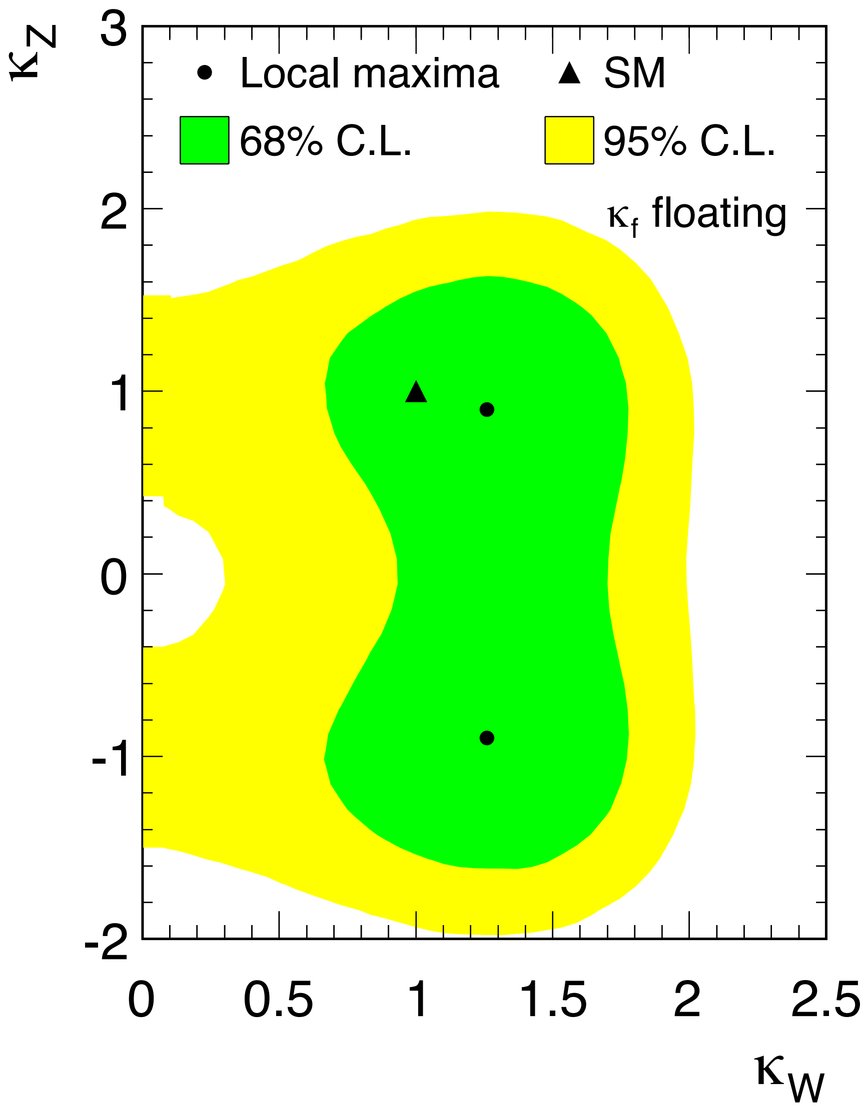


Uniform prior assumed

Large κ_V with small κ_f constrained by trileptons, same-sign dileptons

Large κ_f and small κ_V constrained by ttH→ttbb

Two-Dimensional Constraints: W vs. Z Couplings



Uniform prior assumed

κ_f integrated over ("marginalized")

Less constraint on HZZ than on HWW

All couplings consistent with SM predictions

Summary (1)

- CDF's Searches for the Higgs boson in the SM, SM4, and Fermiophobic models are now finalized
- Publications on the final METbb (HOBIT) search plus the combination are being submitted.
- Previous METbb (SECVTX+JP) analysis is still valid – no mistakes affecting the Summer 2012 result were found.
- Switching to a new b-tagger reclassified events – only 50% overlap with events in the old METbb analysis in the highest-NN_{SIG} region.
- New best-fit cross sections are somewhat lower.
- We must choose the more sensitive analysis: HOBIT METbb is 8% more sensitive than the previous version at m_H=125 GeV/c^2

Summary (2)

Excess of events persists in the SM Higgs search near m_H=125 GeV/c^2.

Higgs boson does not look like those of the FP model, or SM4.

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 channels.

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