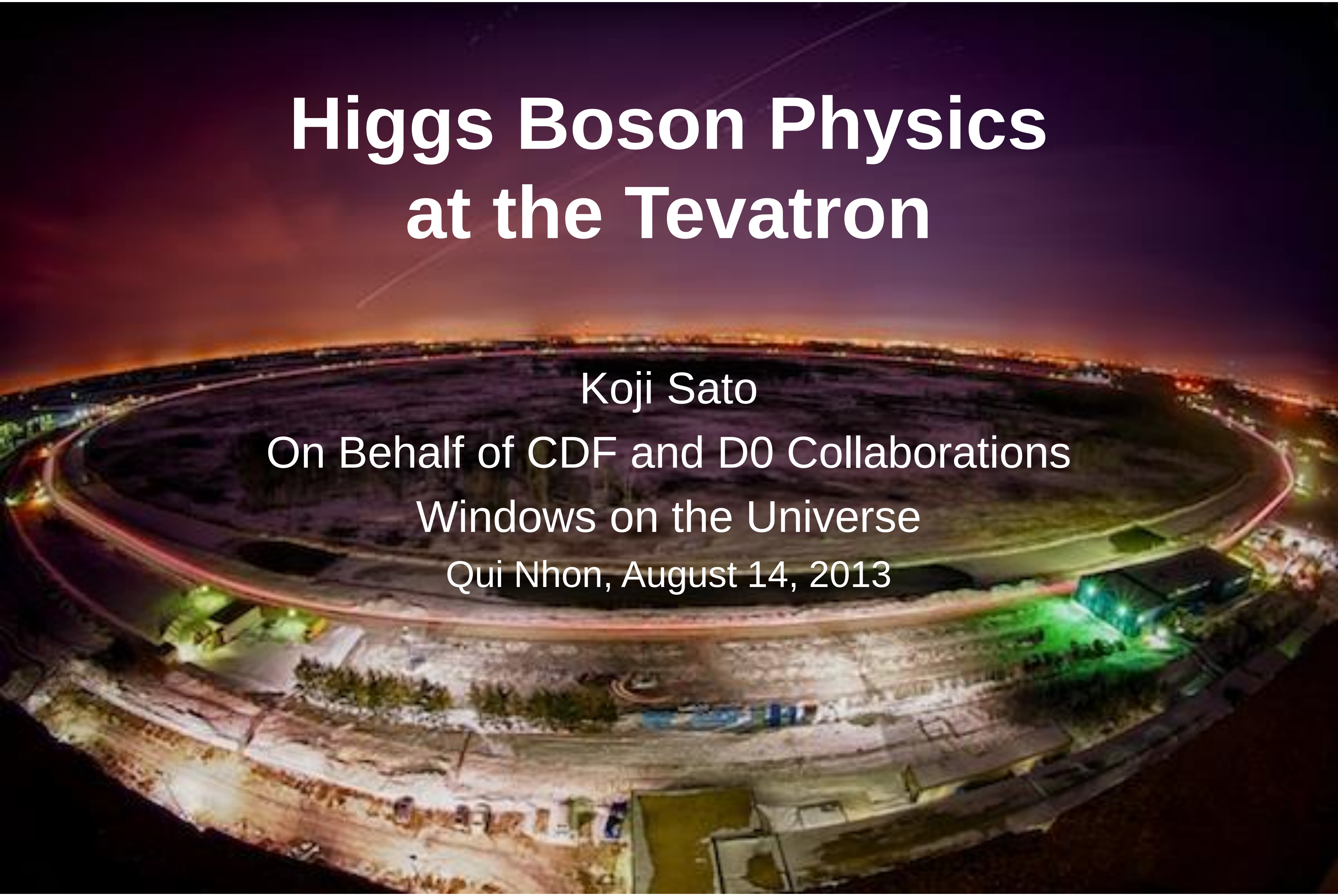
Higgs Boson Physics at the Tevatron

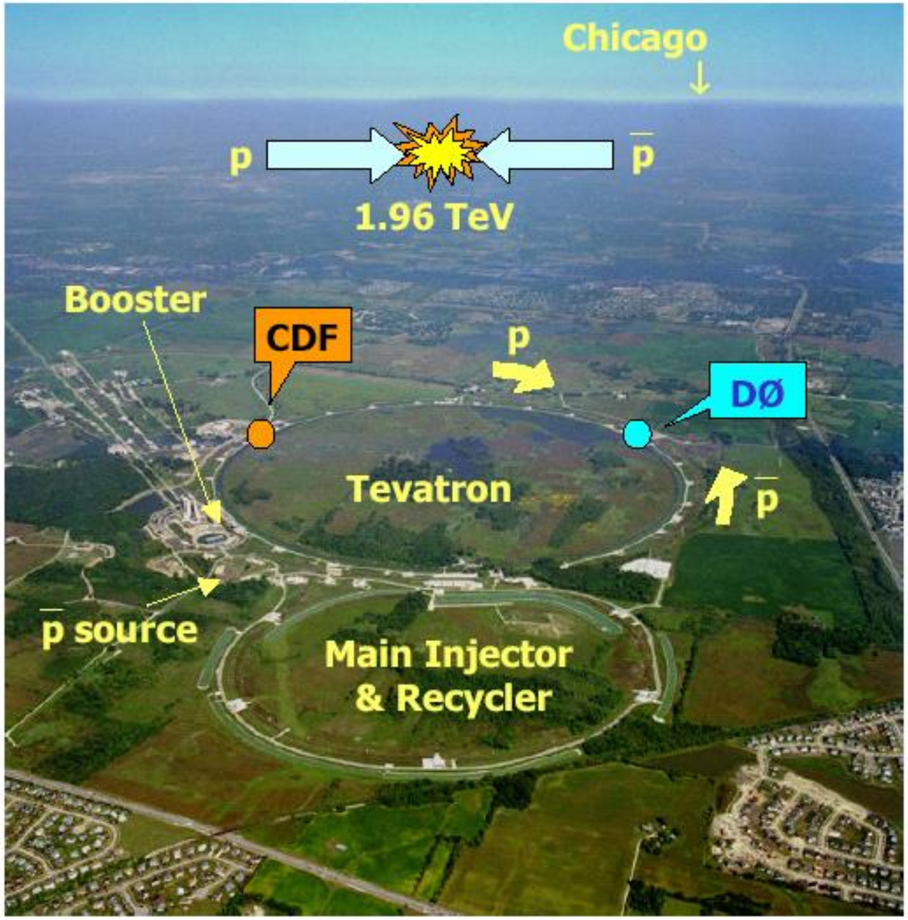
Koji Sato
On Behalf of CDF and D0 Collaborations

Windows on the Universe

Qui Nhon, August 14, 2013



Tevatron Run II

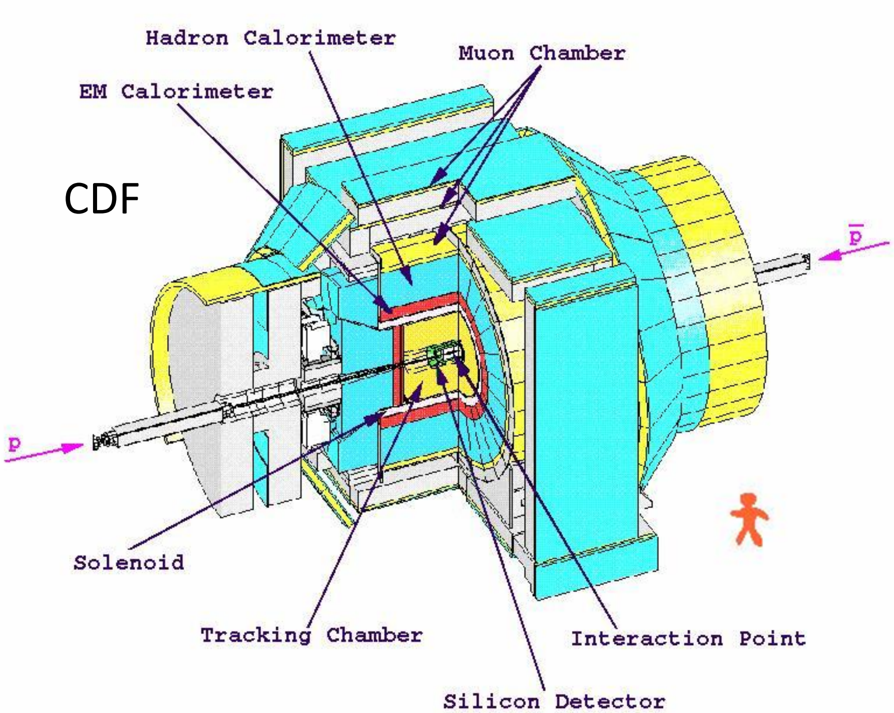


- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV (1.8 TeV in Run I).
- Run II:
  Summer 2001 - Autumn 2011.
- Collisions at world highest energy until Nov 2009.
  - Energy frontier for ∼25 years!!
- Two detectors (CDF and D0) for wide range of physics studies.
- Delivered: 12 fb^{-1}.
  - Recorded by CDF: 10 fb^{-1}.
  - Recorded by D0: 10 fb^{-1}.

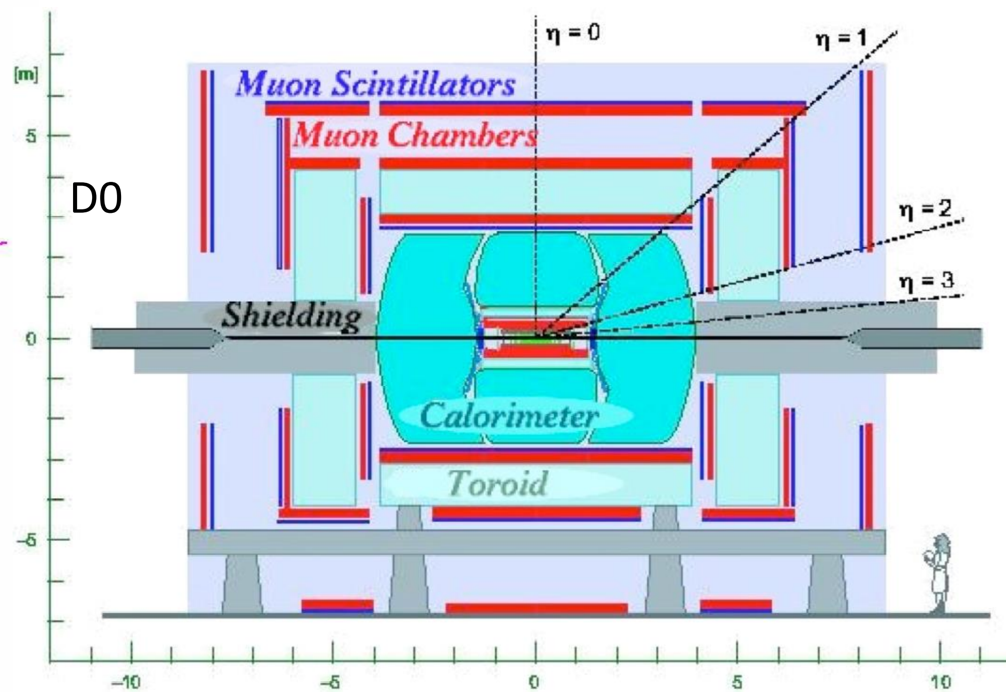
CDF and D0 Detectors

- Both are multipurpose detectors:
  - Top/EWK measurements, Searches for Higgs and New Phenomena, and B physics.
- Precision tracking with silicon in 1.5 (CDF)/1.9 T (D0) solenoid field.
- EM/Had calorimeters for e/γ/jet measurement.
- Outer muon chambers.

CDF



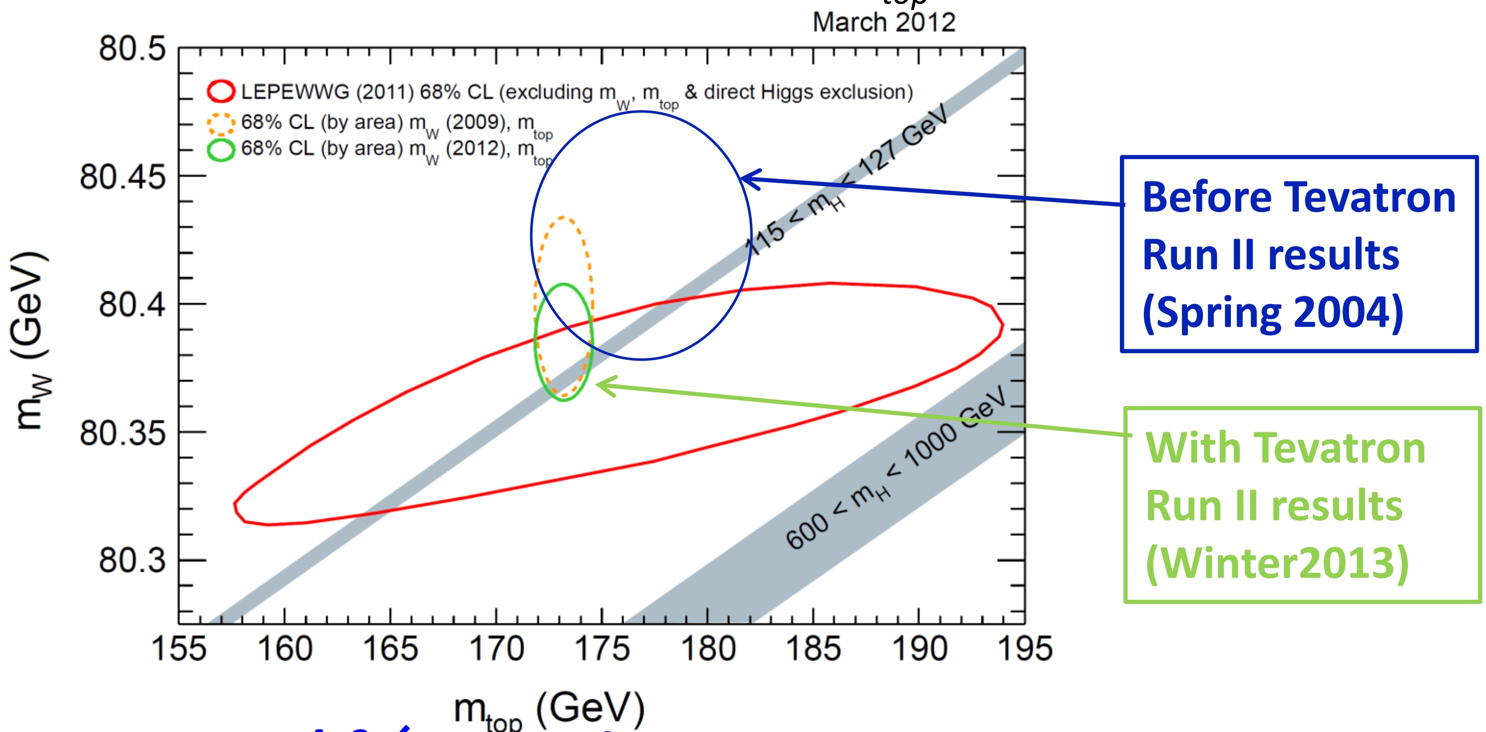
D0



Constraint on Higgs Mass

- Mass of W Boson (World Average):
  Before Tevatron Run II :
  m_W=80.426±0.034 GeV/c²
  With Tevatron Run II results :
  m_W=80.385±0.015 GeV/c²

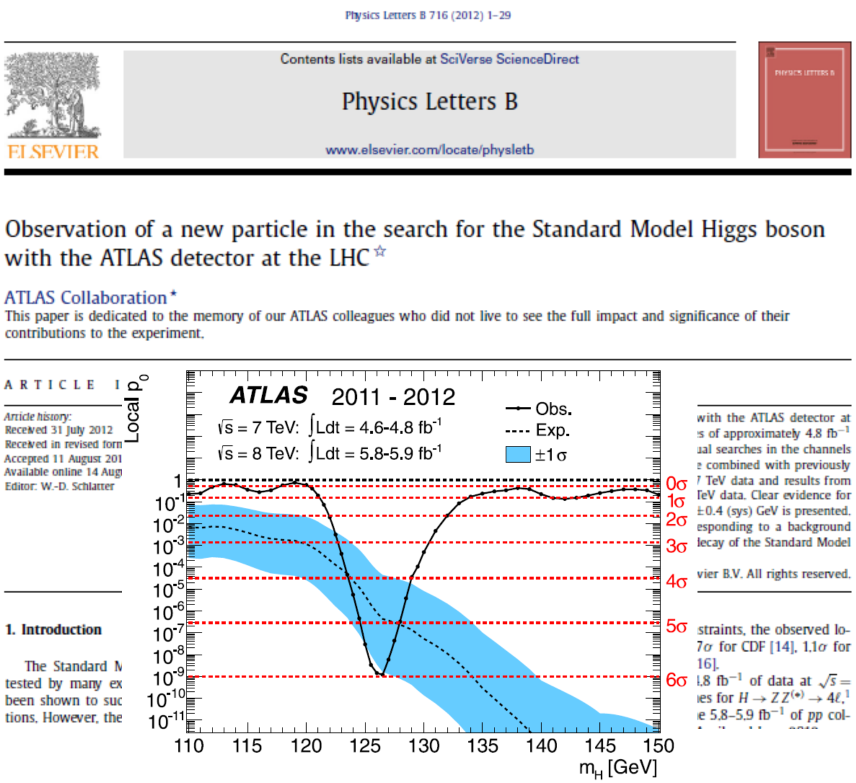
- Mass of Top Quark (World Average):
  Tevatron Run I result :
  $m_{top} = 178.0 \pm 4.3$ GeV/c^2
  With Tevatron Run II results :
  $m_{top} = 173.2 \pm 0.9$ GeV/c^2



M_{higgs} < 152 GeV/c^2 (95% CL) .

....*was* M_{higgs} < 251 GeV/c^2 (95% CL) in Spring 2004.

Higgs Discovery by LHC, Summer 2012


Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

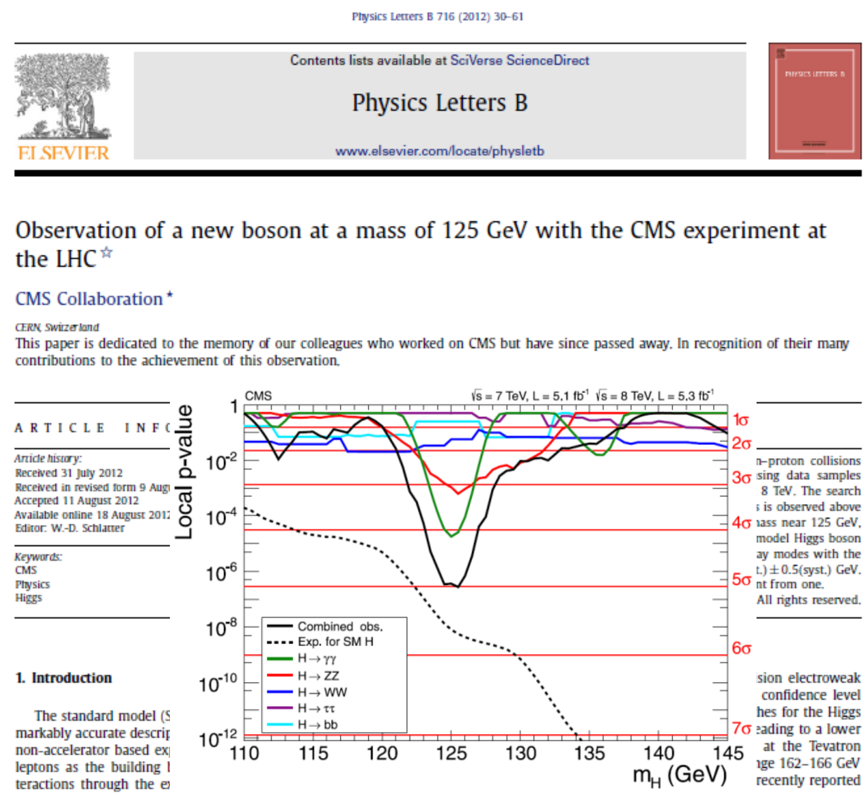
Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.


Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ATLAS: 5.9 σ from Background

CMS: 5.0 σ from Background

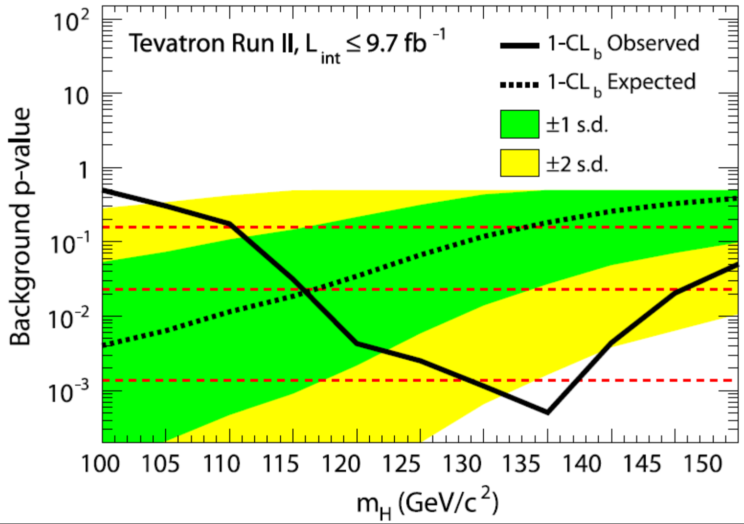
Discovery was driven by $H \rightarrow \gamma\gamma$, ZZ and WW decay modes.

What We Want to Remember!!

Selected for a Viewpoint in *Physics*
PRL 109, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

T. Aaltonen,[12,*] V. M. Abazov,[48,†] B. Abbott,[112,†] B. S. ... xeev,[48,†]
G. Alkhazov,[52,†] A. Alton,[96,†,ff] B. Álvarez Gonzále ... [96,*]
A. Anastassov,[76,*,c] A. Annovi,[34,*] J. Antos,[53,*] G. Ap ... kov,[48,*]
J. Asaadi,[119,*] W. Ashmanskas,[76,*] A. Askew,[74,†] S. A ... no,[119,*]
C. Avila,[7,†] F. Azfar,[66,*] F. Badaud,[13,†] W. Badgett,[76,*] ... urin,[74,†]
S. Banerjee,[31,†] A. Barbaro-Galtieri,[68,*] E. Barberi ... [90,*]
P. Barria,[36c,36a,*] J. F. Bartlett,[76,†] P. Bartos,[53,*] U. B ... n,[87,†]
F. Bedeschi,[36a,*] M. Begalli,[2,†] S. Behari,[90,*] L. Bellantor ... jamin,[109,*]
A. Beretvas,[76,*] S. B. Beri,[29,†] G. Bernardi,[17,†] R. Bern ... inck,[63,†]
P. C. Bhat,[76,†] S. Bhatia,[99,†] V. Bhatnagar,[29,†] A. Bha ... k,[64,*]
... k,[106,*] ... [116,*] ... ss,[76,†] ... escher,[25,†] ... zatu,[4,*]
K. M. Chan,[84,†] A. Chandra,[121,†] E. Chapon,[18,†] G. Chen,[87,†] Y. C. Chen,[6,*] M. Chertok,[69,*] S. Chevalier-T...

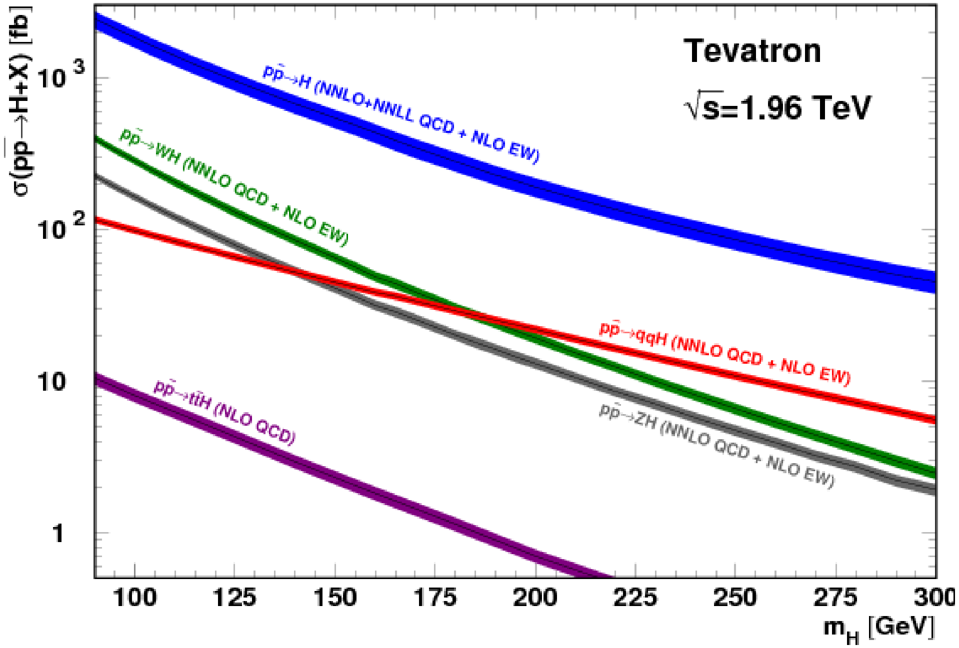


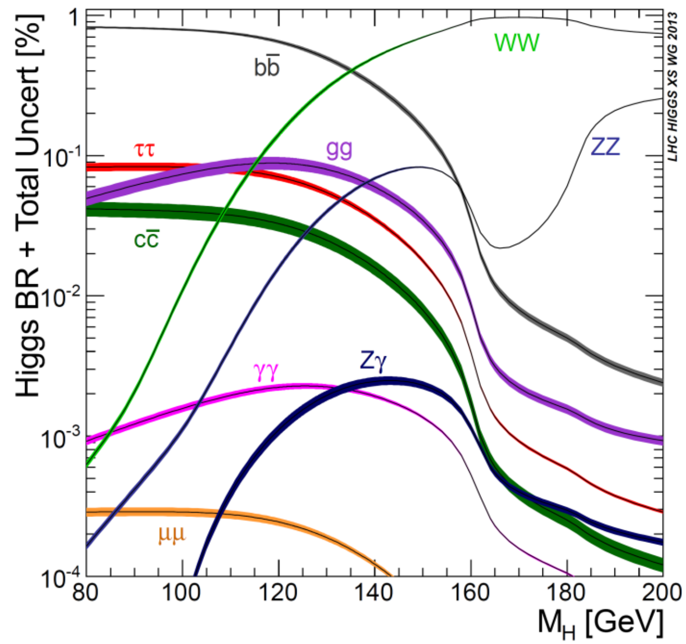
TEVATRON Summer 2012:
Excess at $m_H = 120 - 135$ GeV/c² mass region.
Global significance 3.1 σ from Background in Combination of searches for $H \rightarrow bb$ analyses.
Complementary to LHC results
Discovery was driven by $H \rightarrow \gamma\gamma$, ZZ and WW decay modes.

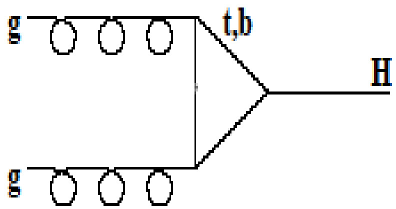
Tevatron Winter 2013 Combination

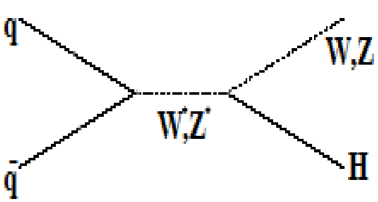
- Analysis updates in a few channels since last Summer.
- Combination of all the available search channels.
- Although we know $m_H \sim 125\ \mathrm{GeV}/c^2$ from LHC results, we present our search results over full mass range.
- Studies of Higgs properties.

SM Higgs Production and Decay at Tevatron









Channels with best sensitivity are:

- m_H<135 GeV (low mass):
  - gg→H→bb is difficult to see.
  - Look for WH/ZH with leptonic vector boson decays.
- m_H>135 GeV (high mass):
  - Easiest to look for H→WW→lνlν.

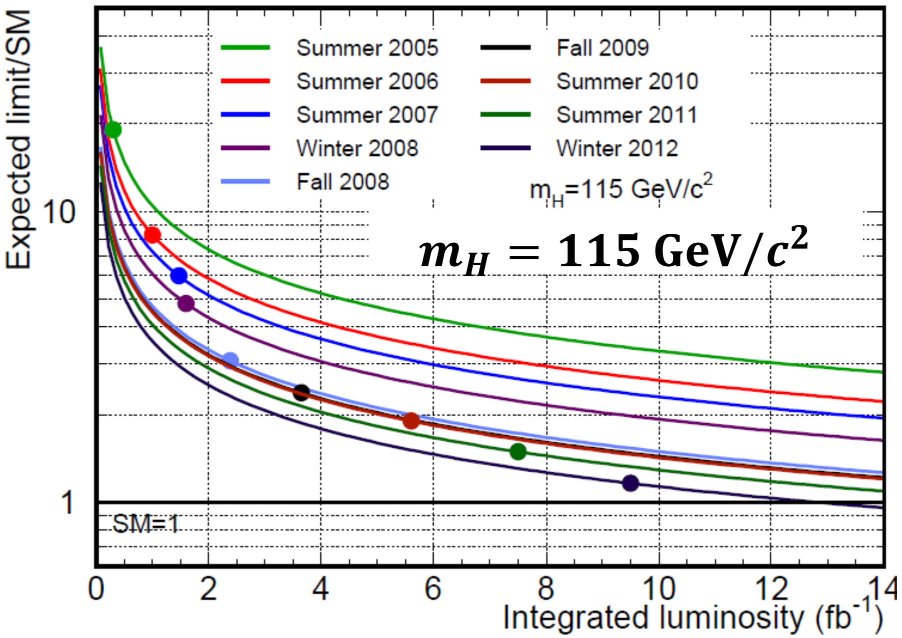
CDF and D0 analyses

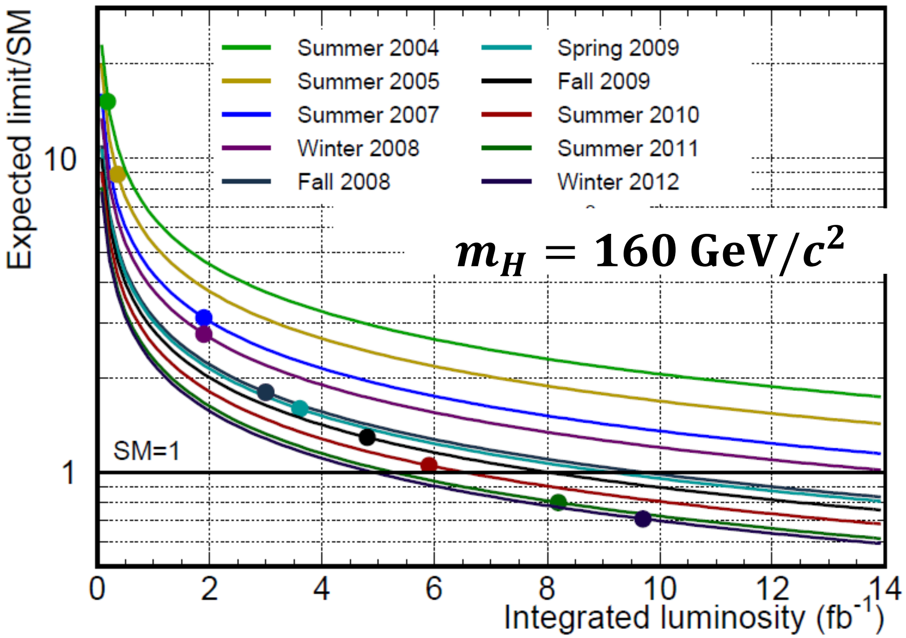
Channel	CDF Luminosity fb^{-1}	D0 Lumiosity fb^{-1}
$WH \to l\nu bb$	9.45	9.7
$ZH \to llbb$	9.45	9.7
$ZH \to \nu\nu bb$	9.45	9.5
$H \to \tau\tau$	6.0	9.6
$WH \to l\nu\tau\tau\ / ZH \to ll\tau\tau$		8.6
$H \to \gamma\gamma$	10.0	9.6
$VH \to jjbb$	9.45	
$ttH \to WWbbbb$	9.45	
$H \to WW \to l^{\pm}\nu l^{\mp}\nu$	9.7	9.7
$H \to WW \to l^{\pm}\nu\tau^{\mp}\nu$	9.7	7.3
$VH \to VWW \to lll + X$	9.7	9.7
$VH \to VWW \to l^{\pm}l^{\pm} + X$	9.7	9.7
$VH \to l\nu jjjj$		9.7
$H \to ZZ \to llll$	9.7	
$H \to WW \to l\nu jj$		9.7

History of Analysis Improvement

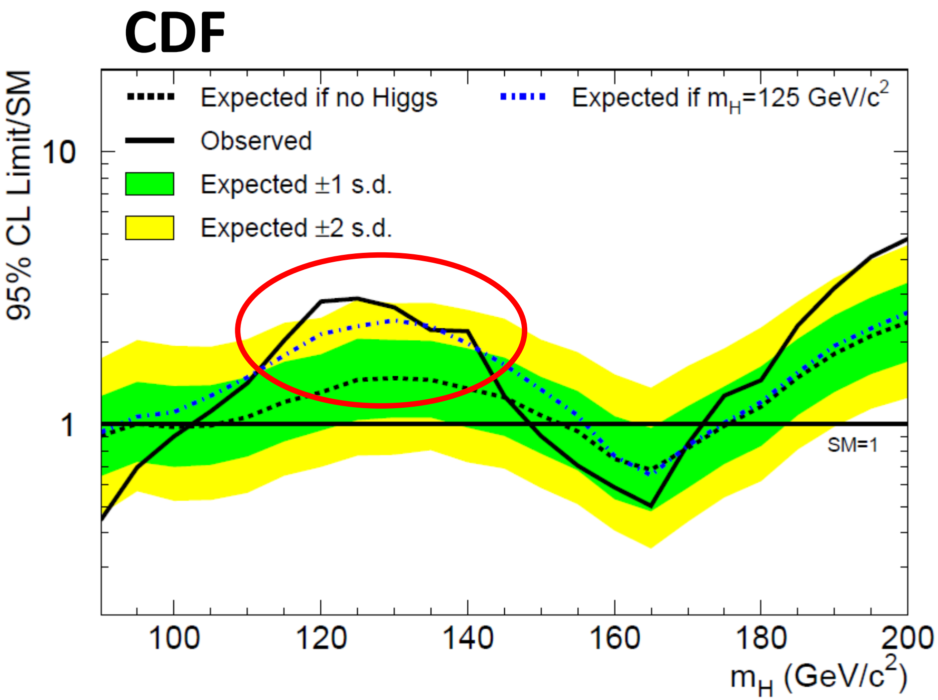
- Tevatron analyses have been constantly improved.
  - Maximize efficiency and acceptance
  - Elaborate use of Multivariate Algorithms (MVAs)
  - Improvement in b-tag algorithms
  - Subdivision of analysis samples into high- and low-purity subsamples.

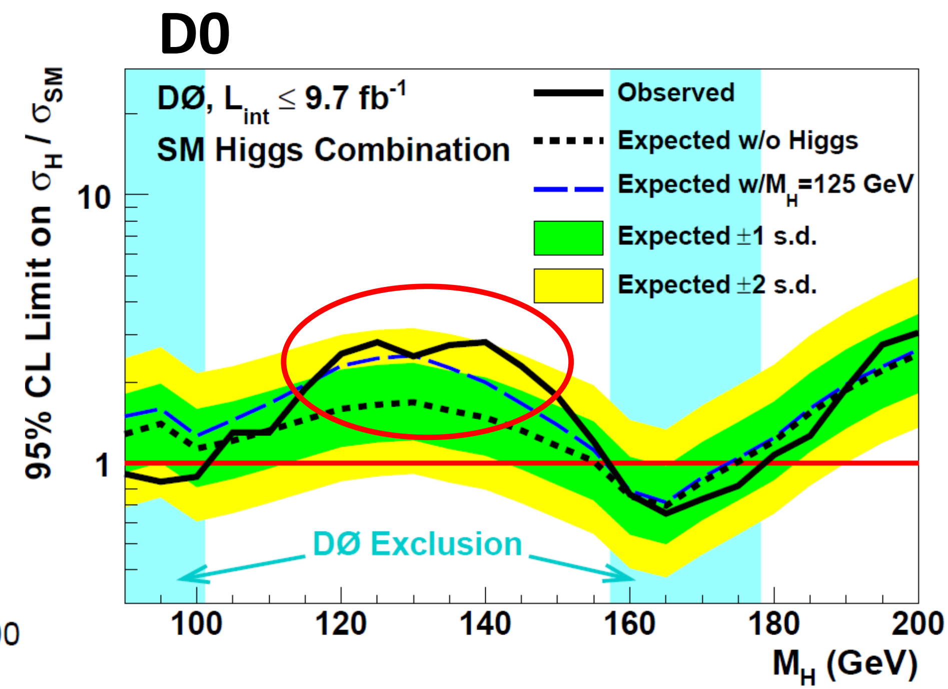
Expected sensitivity for CDF searches: (D0 sensitivities are similar)





CDF and D0: Combined Limit





CDF excludes (95% C.L.):

$90 < m_H < 102$ GeV/c^2

$149 < m_H < 172$ GeV/c^2

Expected exclusion (95% C.L.):

$90 < m_H < 94$, $96 < m_H < 106$ GeV/c^2

$153 < m_H < 175$ GeV/c^2

D0 excludes (95% C.L.):

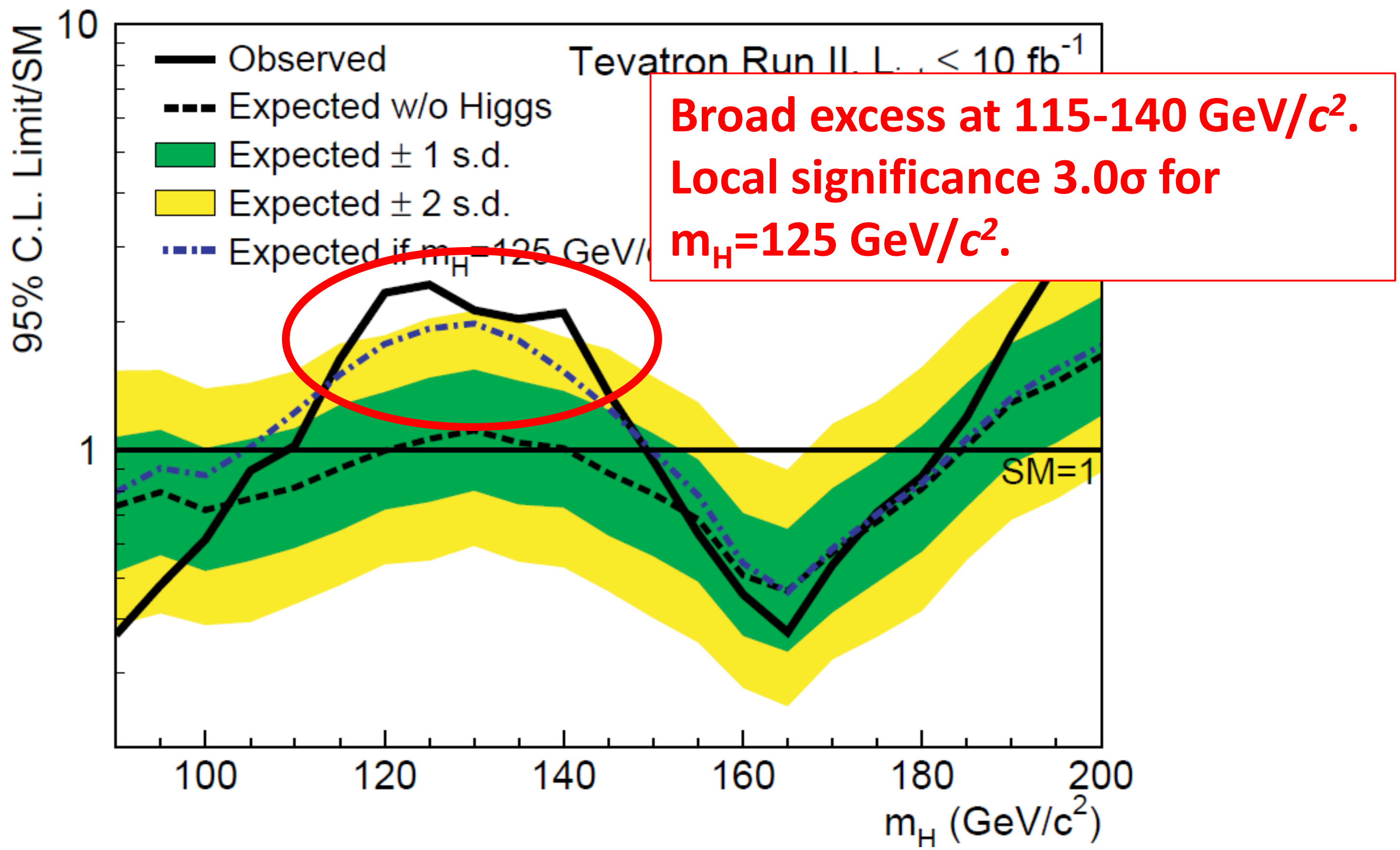
$90 < m_H < 101$ GeV/c^2

$157 < m_H < 178$ GeV/c^2

Expected exclusion (95% C.L.):

$155 < m_H < 175$ GeV/c^2

CDF+D0 Combined Limit



Tevatron excludes:

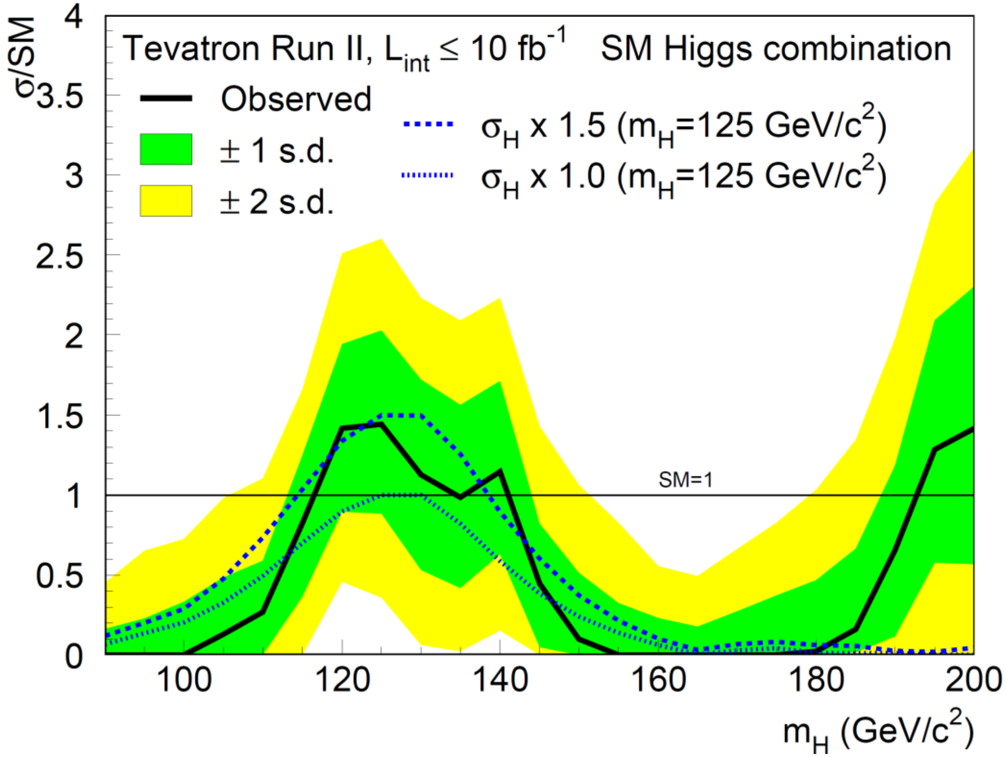
$90<m_H<109$, $149<m_H<182$ GeV/c^2

Expected exclusion:

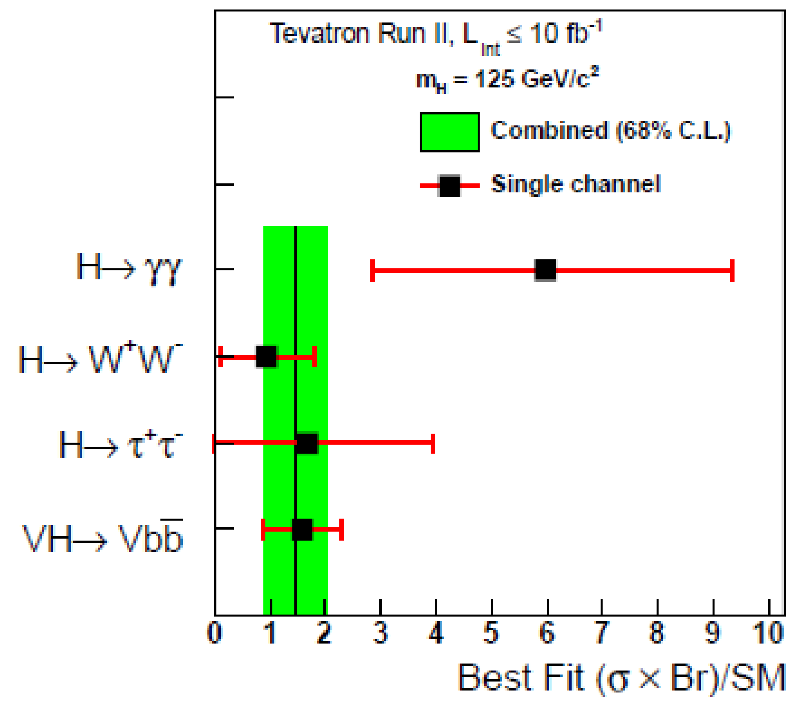
$90<m_H<120$, $140<m_H< 184$ GeV/c^2

Signal Cross Section Best Fit

- Assuming the SM Higgs branching ratio:



- Fit separately by decay mode for $m_H = 125\ \mathrm{GeV}/c^2$:

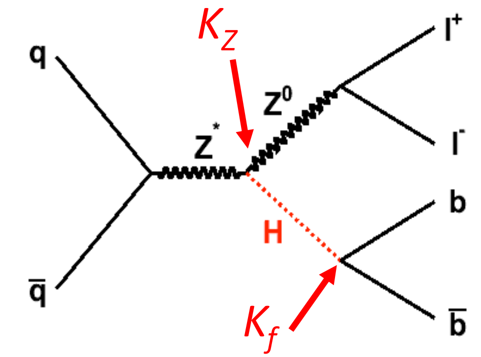


- $\frac{\sigma}{\mathrm{SM}} = 1.44^{+0.59}_{-0.56}$ for $m_H = 125\ \mathrm{GeV}/c^2$.
- Consistent across different decay modes.

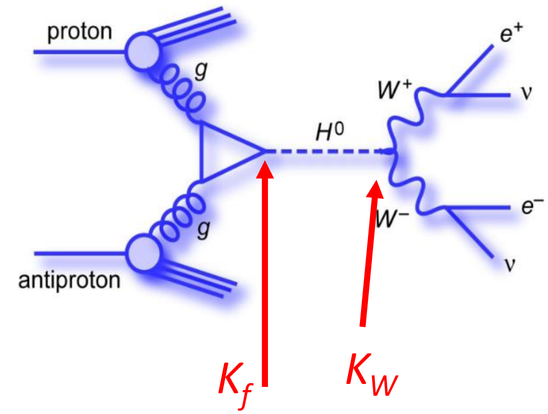
Studies of Higgs Couplings

- Coupling scale factor w.r.t. SM:
  - κ_f : Fermion coupling *Hff*
  - $\kappa_W, \kappa_Z, \kappa_V$: Boson couplings *HWW, HZZ, HVV*

- $\boldsymbol{\sigma(VH) \cdot Br(H \to bb) = \kappa_V^2\ \kappa_f^2 \times (\sigma \cdot Br)_{SM}}$
- $\boldsymbol{\sigma(gg \to H) \cdot Br(H \to VV) = \kappa_f^2\ \kappa_V^2 \times (\sigma \cdot Br)_{SM}}$



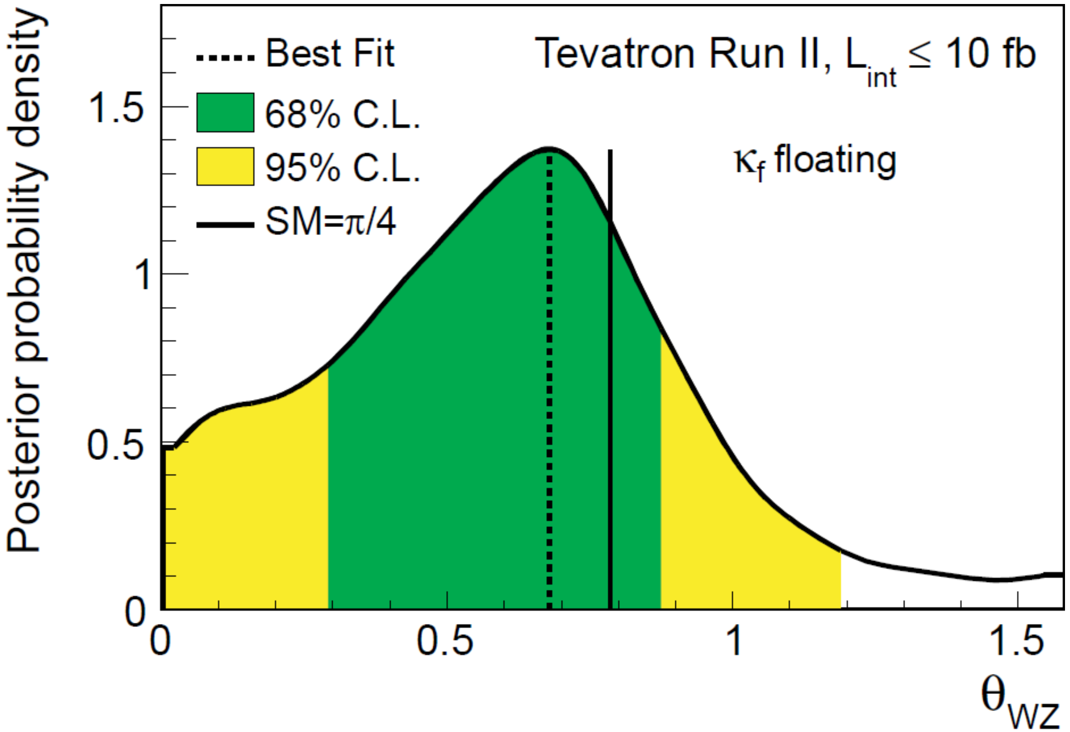
- Follow prescription of LHC Higgs Cross Section Working Group arxiv:1209.0040.
- Assume a SM-like Higgs particle of 125 GeV.



Test of Custodial Symmetry

- κ_f floating.
- Compute posterior probability density for

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



$$|\theta_{WZ}| = 0.68^{+0.21}_{-0.41}$$

$$\boldsymbol{\kappa_W/\kappa_Z = 1.24^{+2.32}_{-0.42}}$$

Constraint on *HVV* and *Hff* Couplings

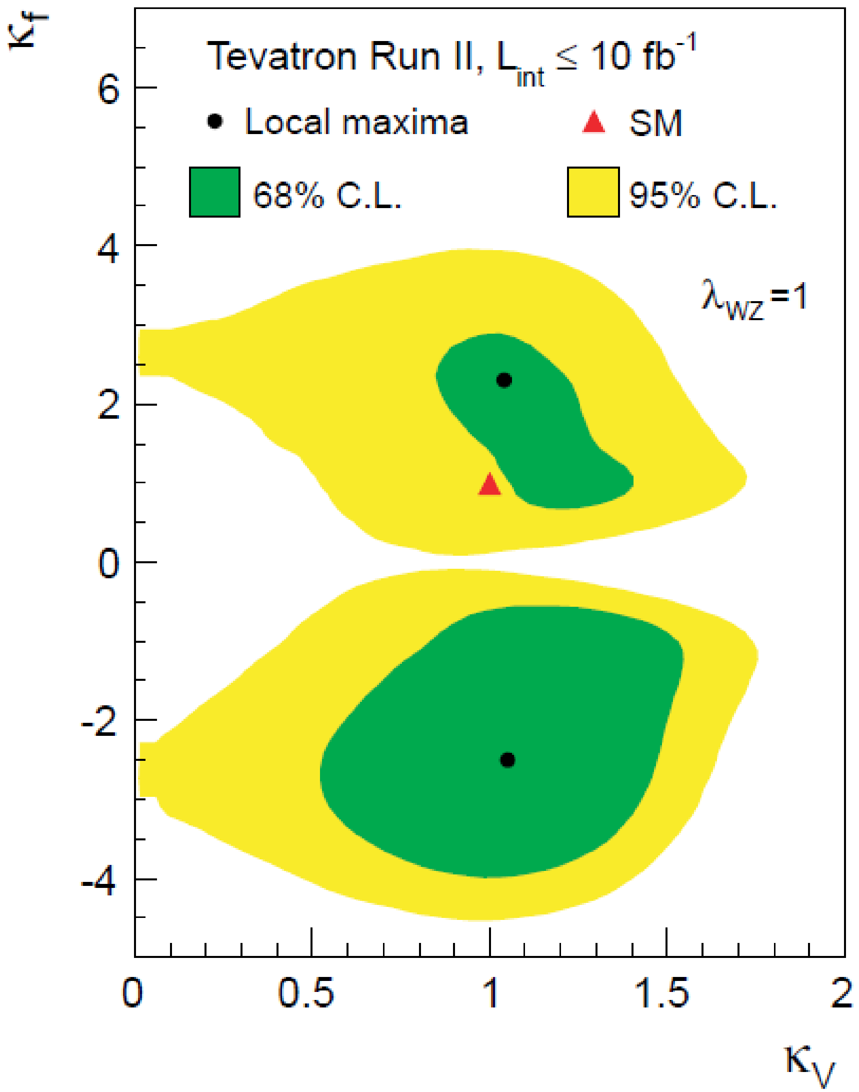
- Assuming:

  $$\kappa_W = \kappa_Z \equiv \kappa_V$$

- Result is consistent with SM.
- Preferred regions around

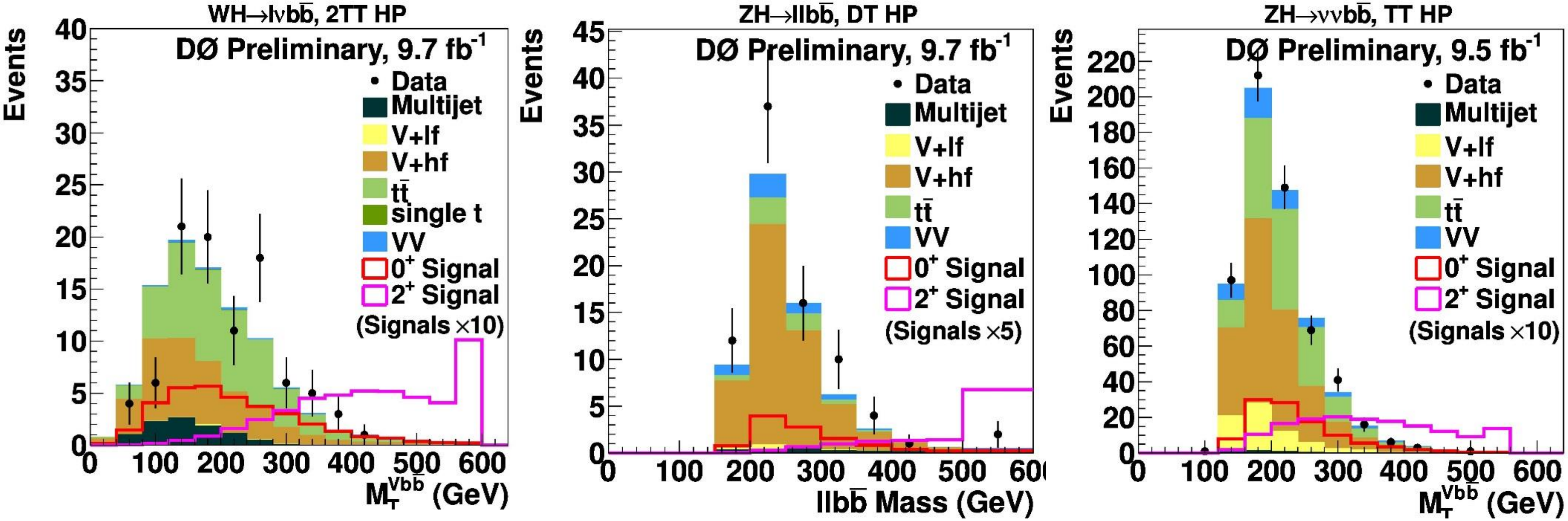
  $$\left(\kappa_V, \kappa_f\right) = (1.05, -2.40), (1.05, \ \ 2.30)$$

- Negative values preferred for κ_f due to $H \rightarrow \gamma\gamma$ excess.



D0 Spin and Parity Measurement

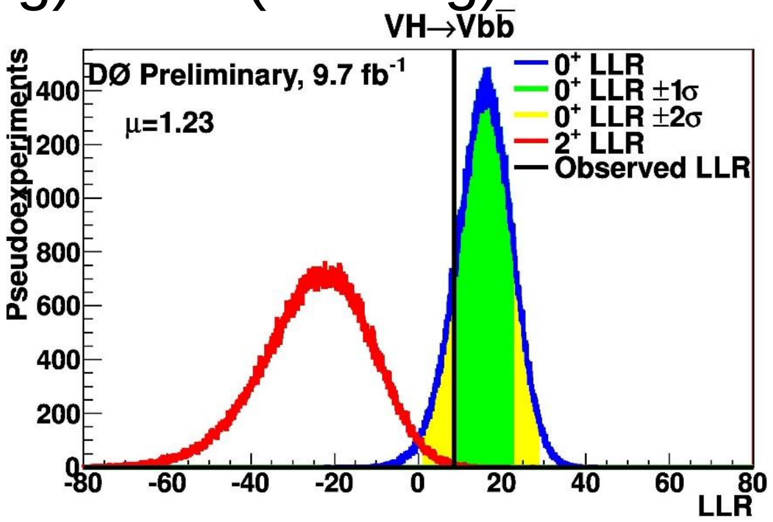
- LHC results in bosonic decay modes favor $J^P = 0^+$.
- Tevatron sensitive in $b\bar{b}$ decay mode.
  - Visible mass of $Vb\bar{b}$ system is sensitive to J^P assignment. - J. Ellis et al., JHEP 1211, **134** (2012)



D0 Spin and Parity Measurement 2

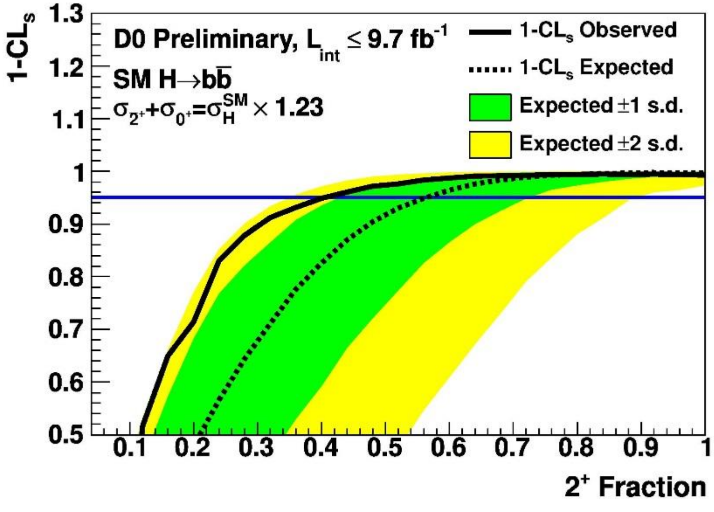
- $LLR = -2\log\frac{L(H1)}{L(H0)}$, H1=($2^+$+bkg) / H0=($0^+$+bkg).

Exclude $J^P = 2^+$ at 99.9% C.L.
(in favor of 0^+).



- Suppose excess is admixture of 0^+ and 2^+ particles:

Exclude 2^+ fraction $f_{2+} > 0.42$
at 95% C.L (in favor of pure 0^+).



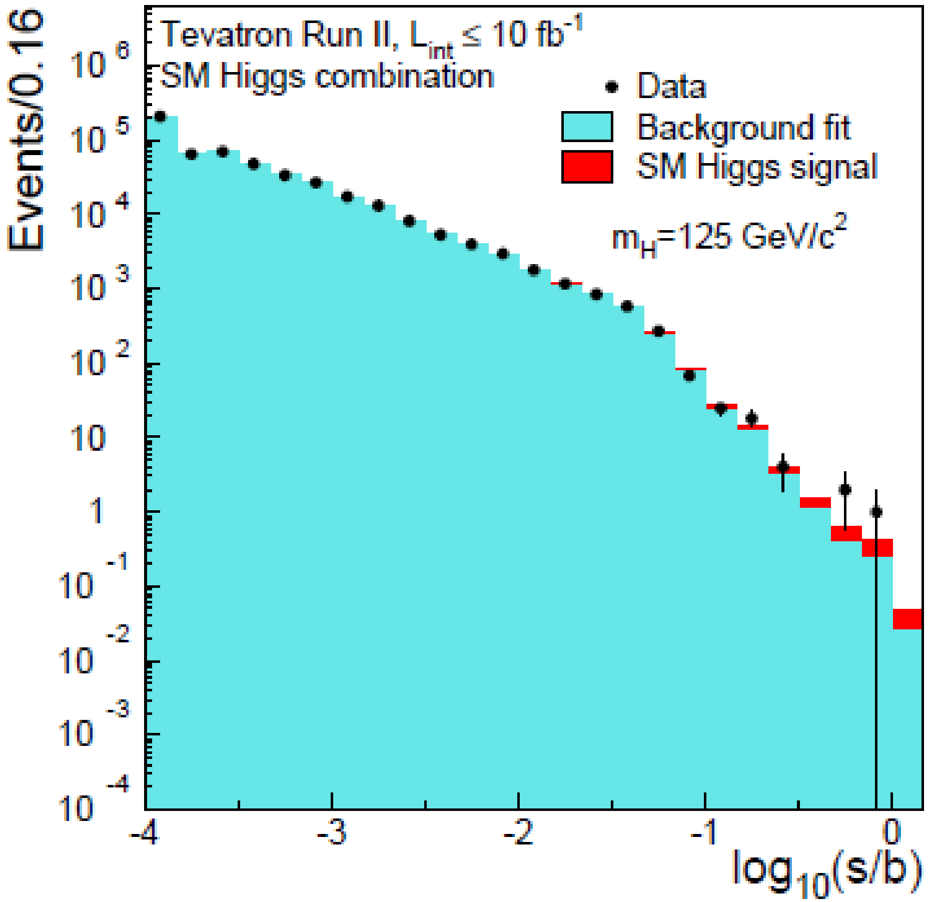
Summary

- Extensive search for Higgs boson with full Tevatron dataset.
  - Analyses evolved through Run II to state of art.
  - Excluded: $90<m_H<109$, $149<m_H<182$ GeV/c^2 (95% C.L.)
- Observed a broad excess in $115<m_H<140$ GeV/c^2.
  - Higgs Mass consistent with LHC.
  - 3.0 standard deviations at $m_H = 125\ \mathrm{GeV}/c^2$.
  - Excess is shared between CDF and D0.
  - Excess mainly from $H \rightarrow b\bar{b}$.
  - $\frac{\sigma}{\mathrm{SM}} = 1.44^{+0.59}_{-0.56}$ for $m_H = 125\ \mathrm{GeV}/c^2$.
- Studies on Higgs couplings to fermions and bosons
  - Consistent with SM expectations.
  - Complementary to LHC measurements.
- Spin/parity studies
  - D0 excludes $J^P = 2^+$ at 99.9% C.L.
  - Tevatron combination of spin/parity study is upcoming!

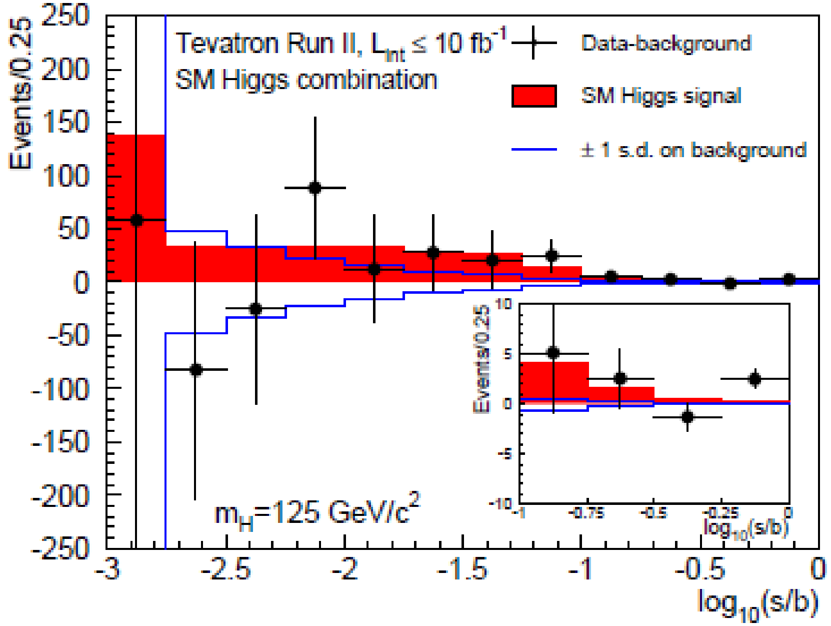
Backup

Distribution of the Candidate Events

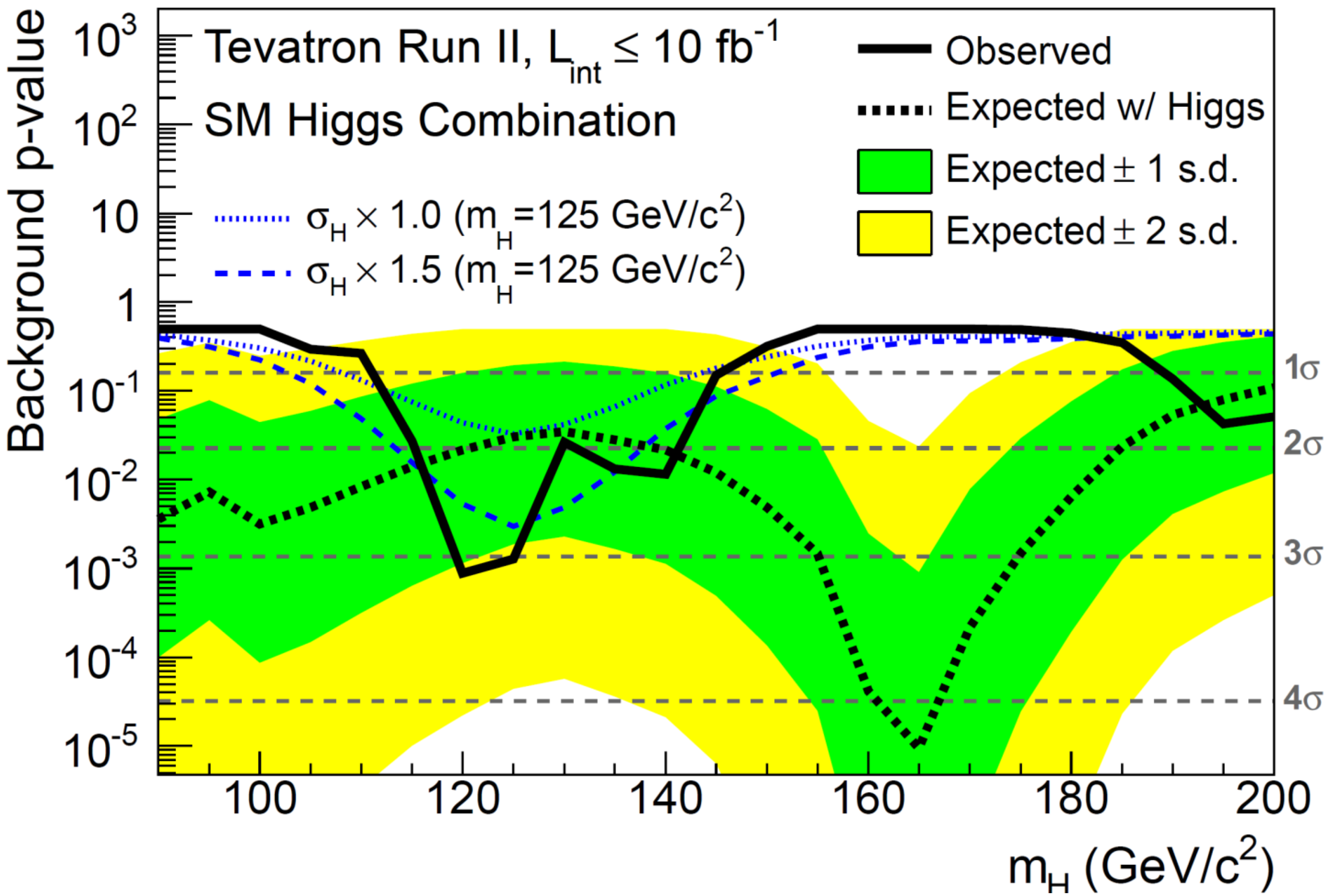
Candidate events in all the combined analyses:



Data - Background

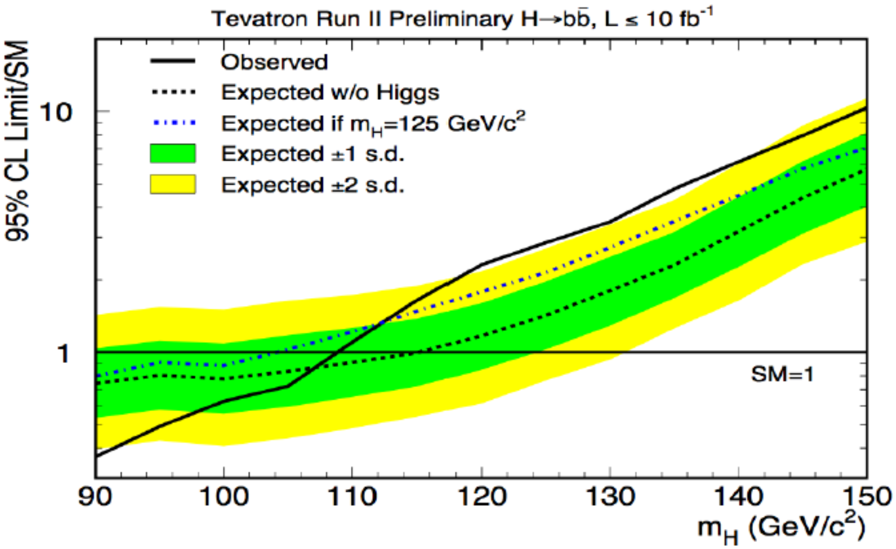


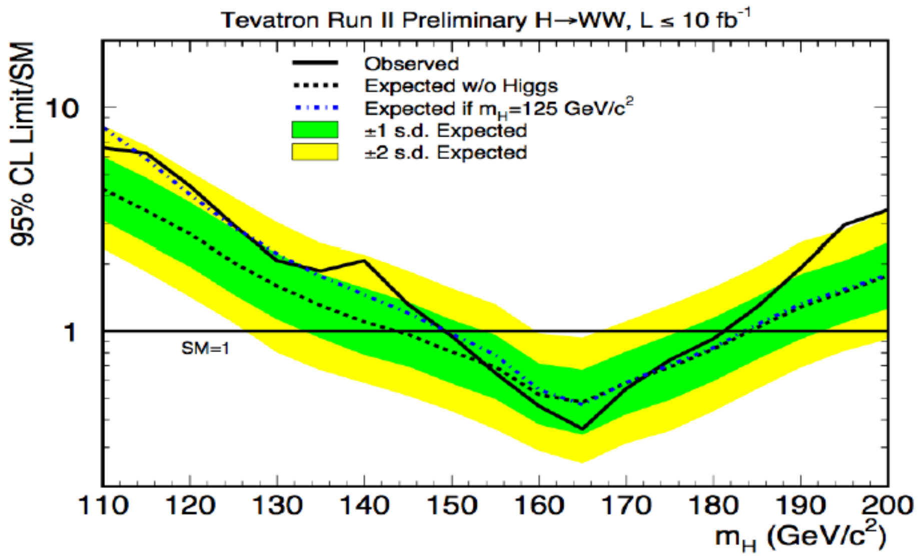
P-value of the Tevatron Combination

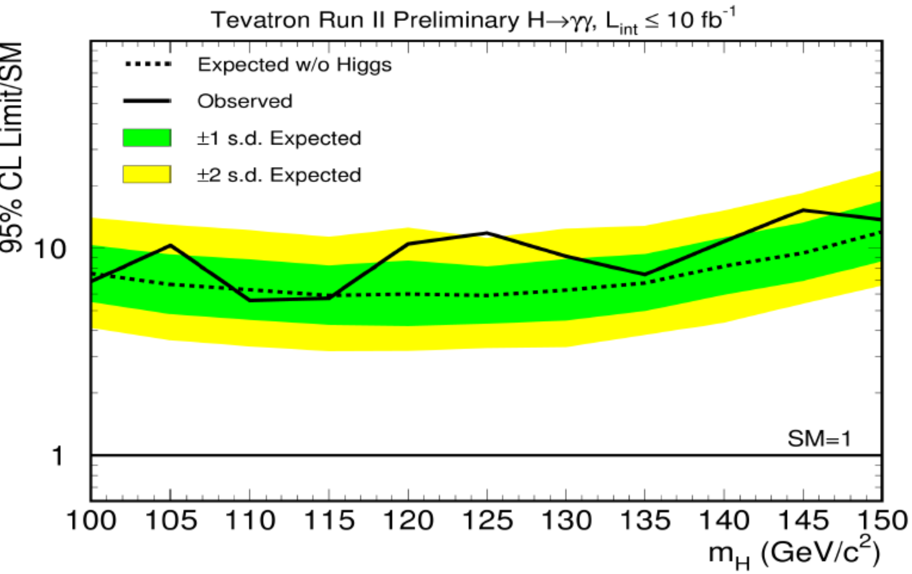


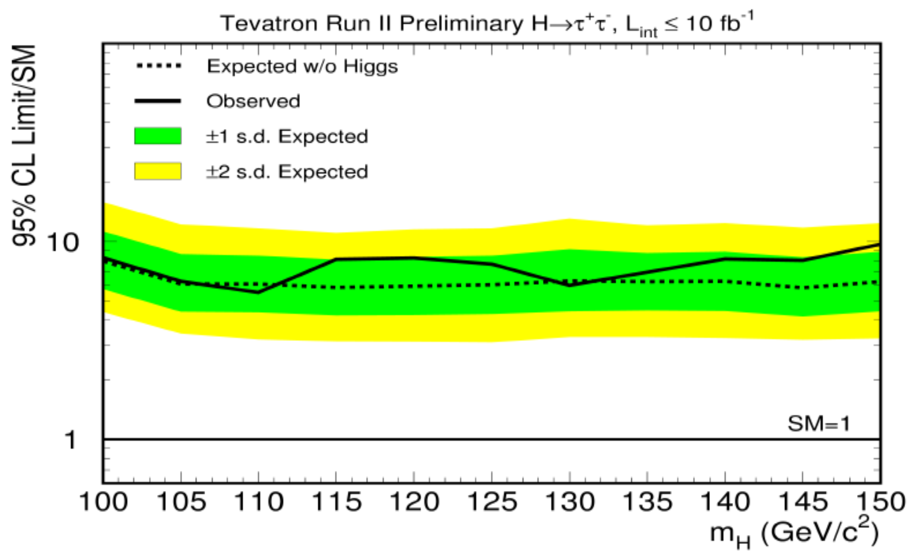
- 3.0 standard deviations at $m_H = 125\ \mathrm{GeV}/c^2$.

Tevatron Combination by Channel

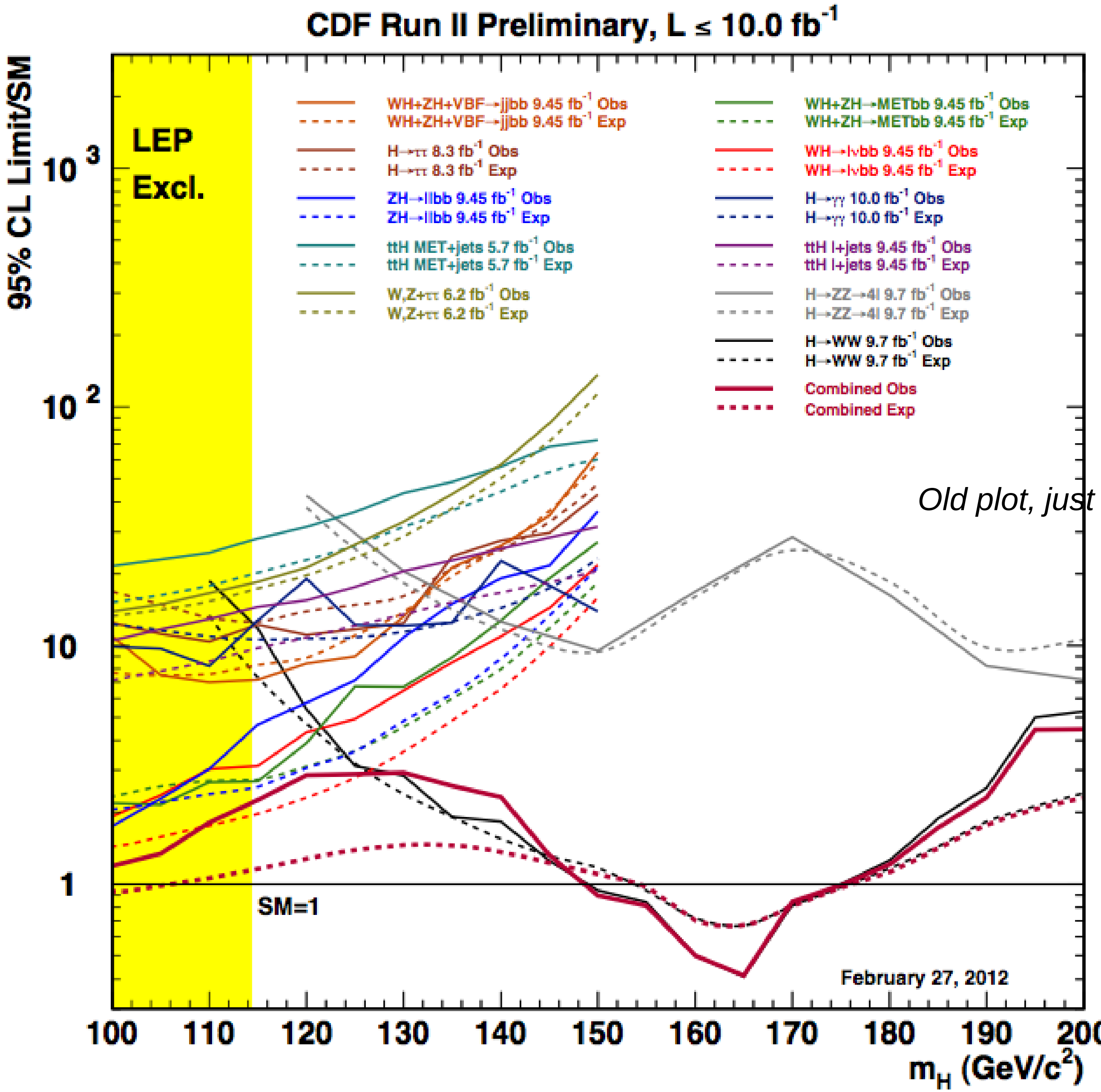






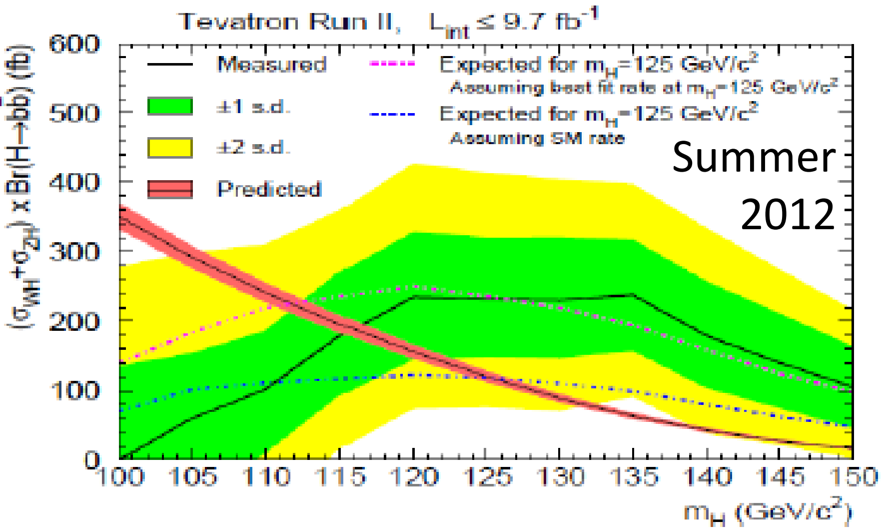


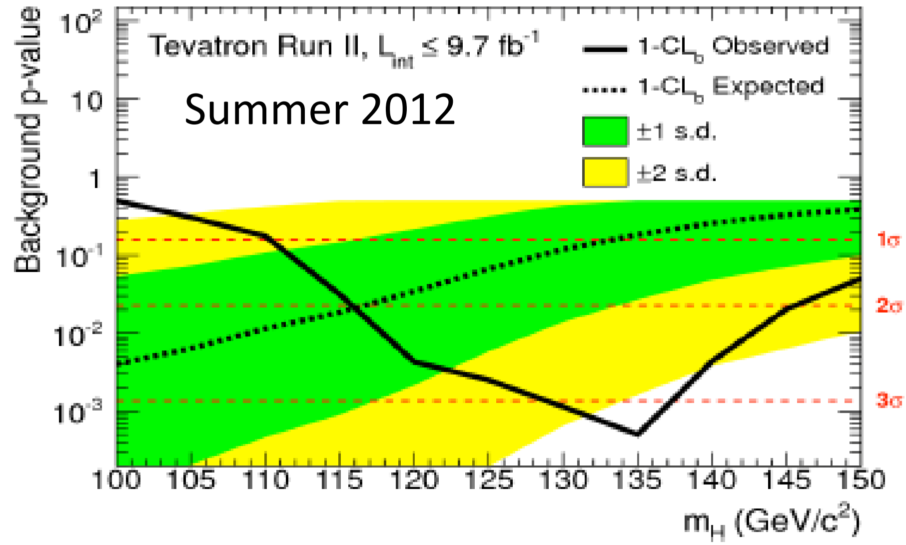
Sensitivity of Individual Channel



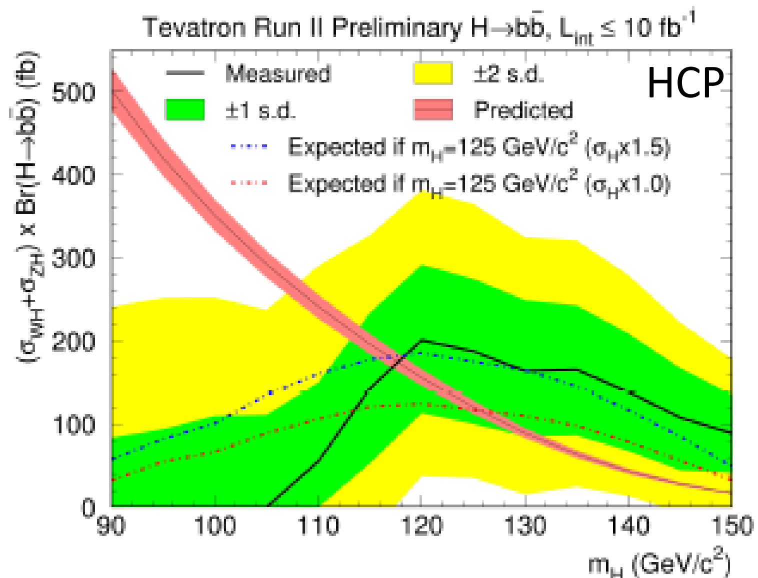
Old plot, just for illustration purposes

Tevatron H→bb Results, PRL 109,071804(2012)

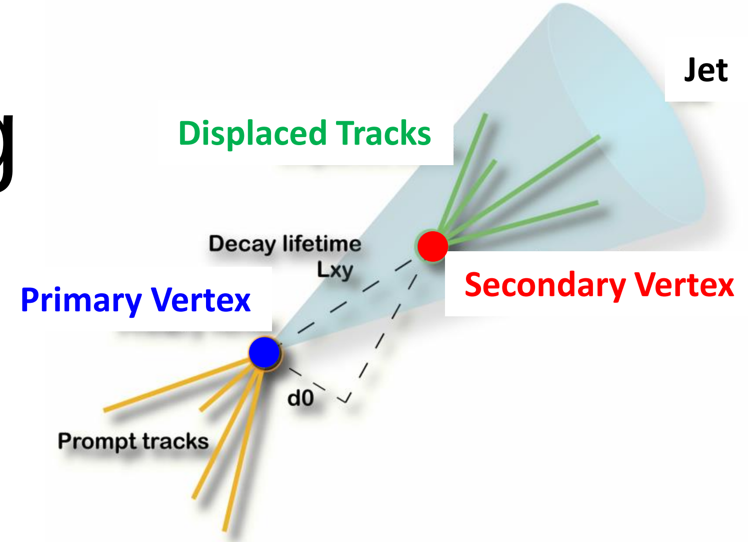




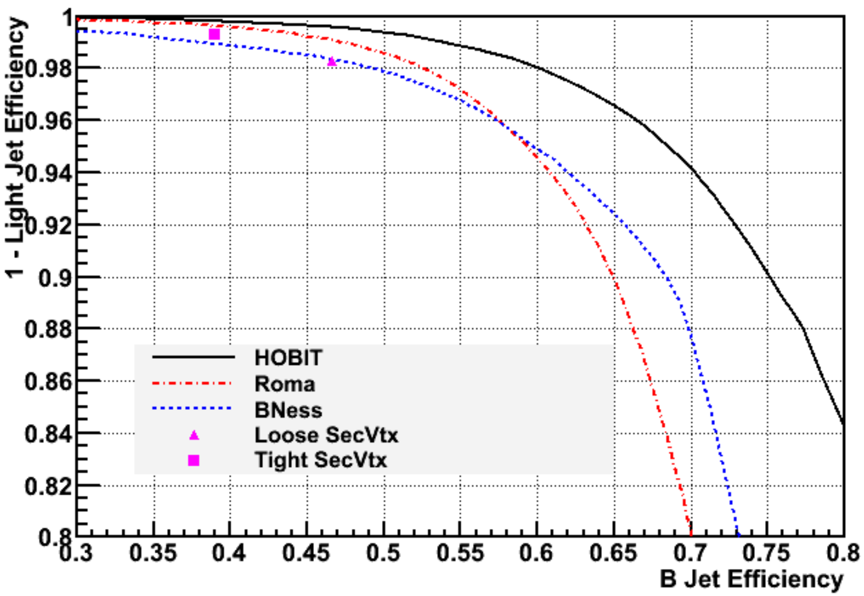
- Last Summer:
  - σ_{VH}=0.23+-0.09pb (SM:0.12+-0.01pb)@125
  - Local max p-value=3.3σ @135GeV(global p-value=3.1σ) and p-value=2.8σ @125 GeV
- HCP:
  - σ_{VH}=0.19+-0.09 pb, consistent with the summer results.
  - We find no significant issues with the previous metbb analysis and stay firmly behind last summer published results.

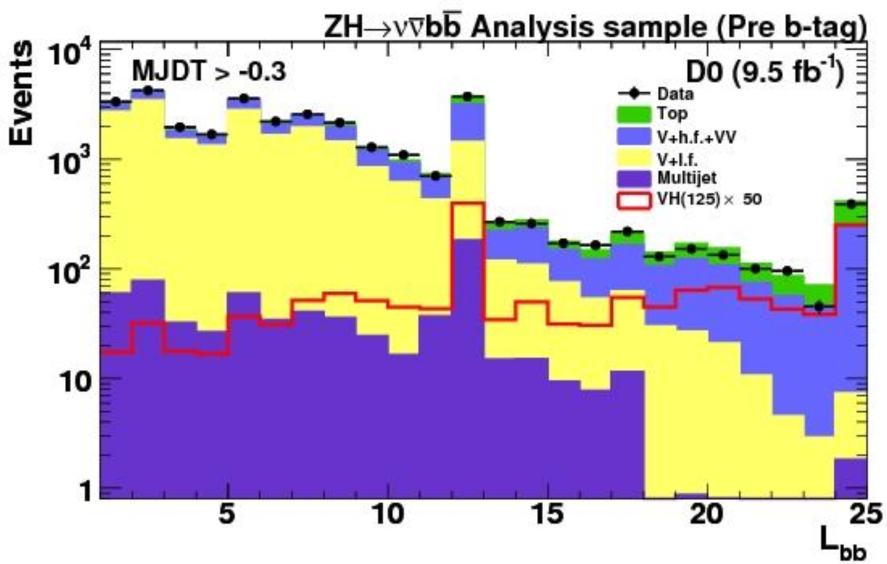


Improved *b*-tagging



CDF and D0 combine information of secondary vertex and tracks within jet cone by MVA (NN and BDT).



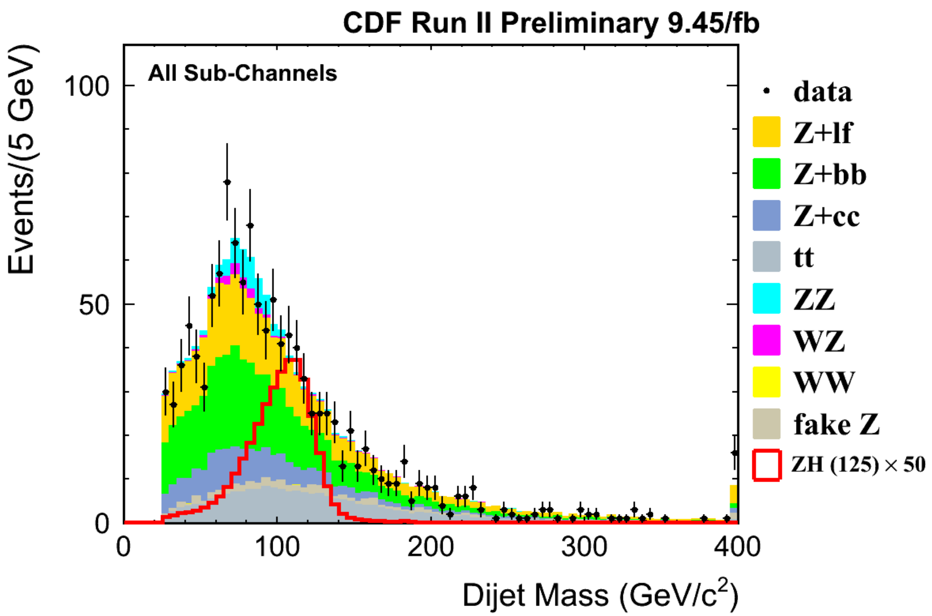


Light Flavor Eff.	HOBIT Eff.	SecVtx Eff. (old tagger)
0.89%	42%	39%
8.9%	70%	47%

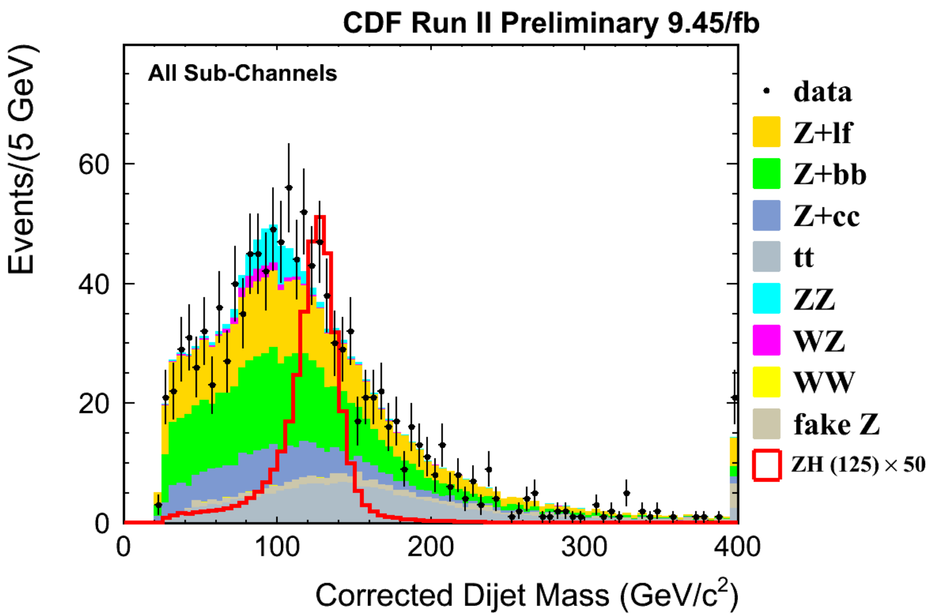
Light Flavor Eff.	Lb Eff.
0.5%	50%
4.5%	70%

B-jet energy correction by NN (CDF llbb channel)

Before NN Correction:

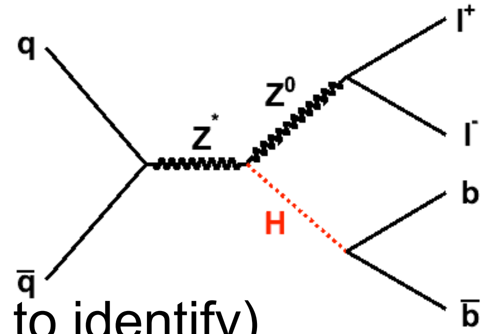


After NN Correction:

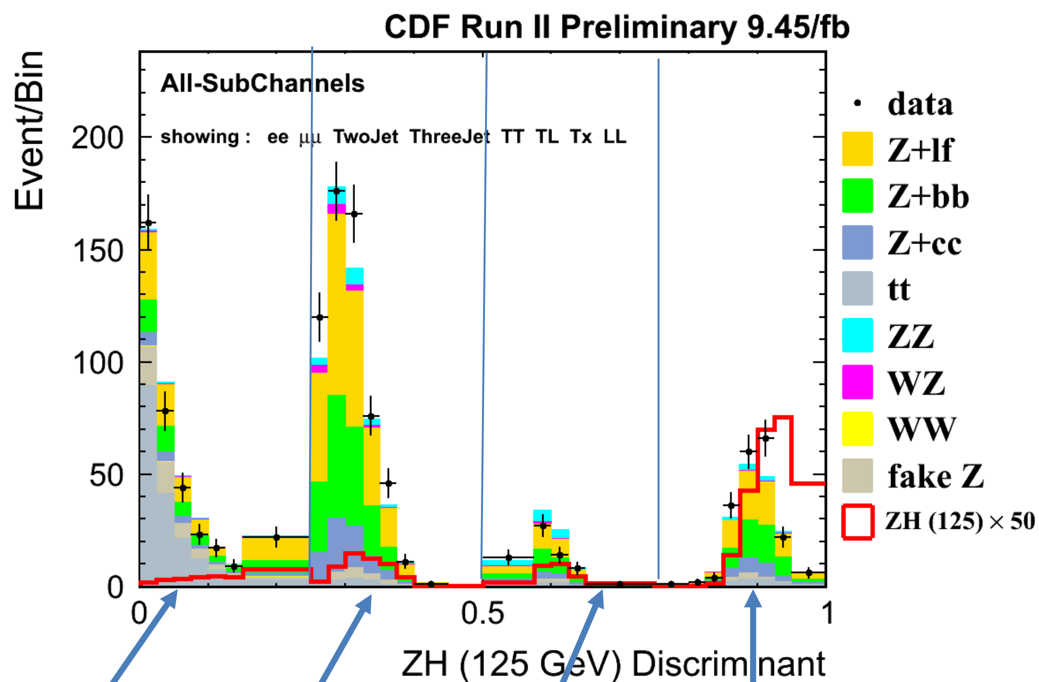


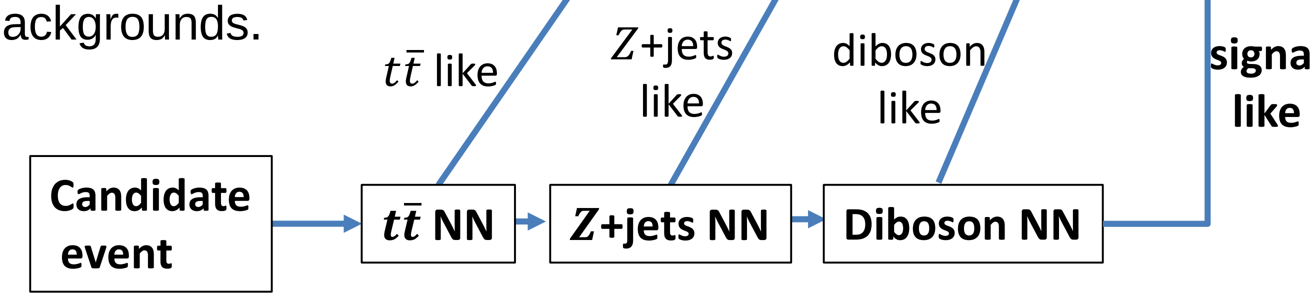
Resolution on $m_H \sim 11\%$

CDF: $ZH \rightarrow llbb$ Analysis



- e^+e^- or $\mu^+\mu^-$ + 2 or 3 jets.
- e /μ trigger + MET trigger (for μ's which trigger failed to identify).
- NN B-tagging algorithm.
  - Two operation points (T/L).
  - Subdivision of events to 4 b-tag categories (TT/TL/Tx/LL)
- Trained 3 NN to further subdivide analysis sample.
  - Separate signal from $t\bar{t}$, Z+jets, diboson.
- Final discrimintnt NN trained to separate signal from all backgrounds.





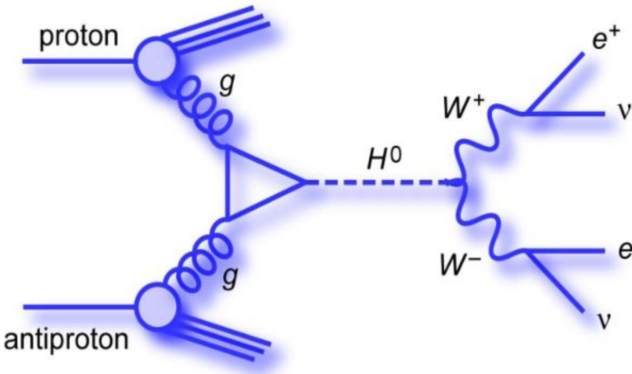
Systematics (CDF *llbb* channel)

Source	%
Luminosity	6
Trigger efficiency	1-5
Lepton energy scale	1.5
ISR/FSR	1-15
B-tag efficiency	5-20
Jet energy scale	5-15
Signal xsec/br	5
Bkgd. Normalization	6-40

Bkgd. Process	%
Mis-ID Z	50
$Z + b\bar{b}/c\bar{c}$	40
$t\bar{t}$	10
Diboson	6

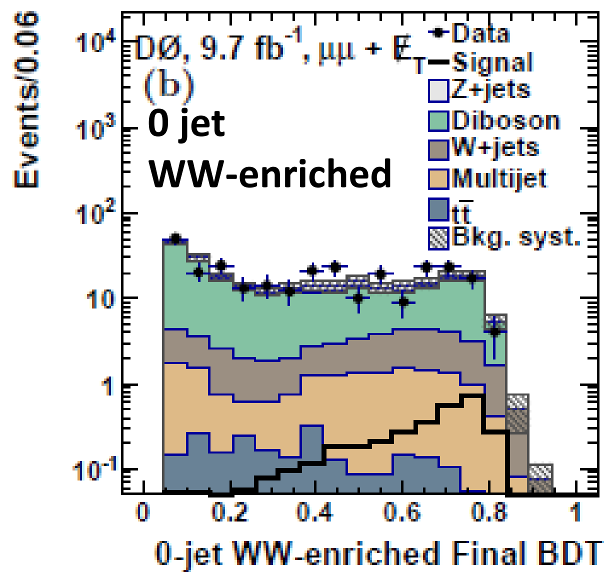
- The effect of Jet Energy Scale on the distribution shape is also considered.
- Sysyrmstic uncertainty degrade sensitivity to *ZH* signal by approximately 13%.

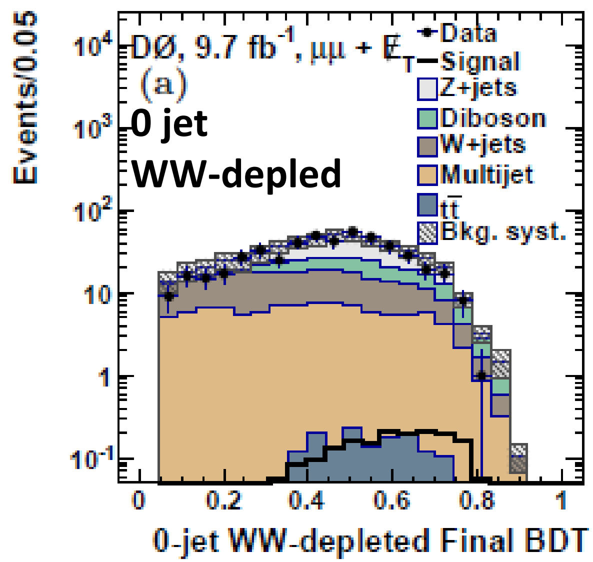
D0: $H \to W^+W^- \to l^+l^- + MET$ Channel

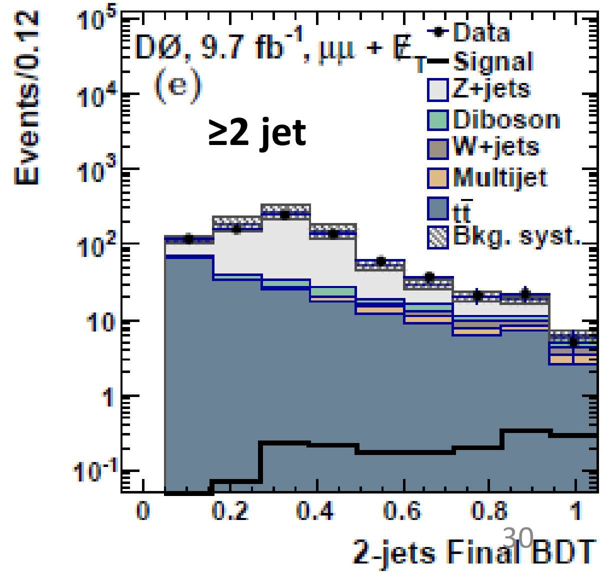


- e^+e^-, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ pair within $M_{ll} > 15$ GeV.
- BDT to reject $Z/\gamma^* \to ll$ in e^+e^-, $\mu^+\mu^-$ events.
- $gg \to H, WH, ZH, VBF$ are considered as signal.
  – Events with different jet multiplicity have different s/b composition.
  – Separately analyze 0, 1, ≥2 jet bins.
- Subdivision of sample into *WW*-enriched/depleted by *WW*-BDT.
- Train a final BDT discriminant against all background.

Distributions of the Final discriminant (only showing 3 $\mu\mu$ channels out of 14 orthogonal subchannels):







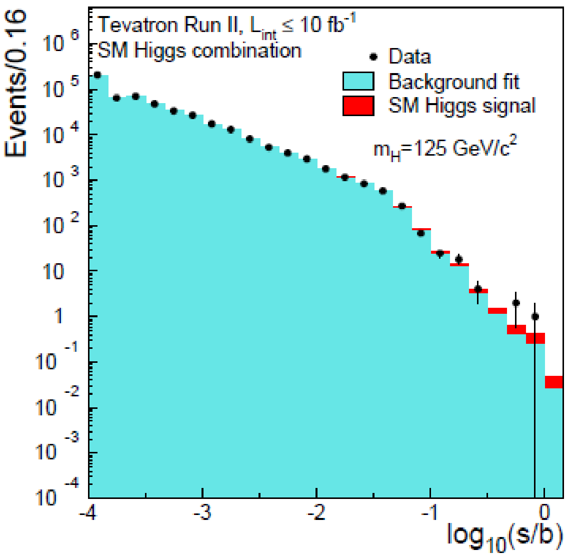
General Strategy for Improved Sensitivity

Analysis improvements we just reviewed are implemented for most of the channels.

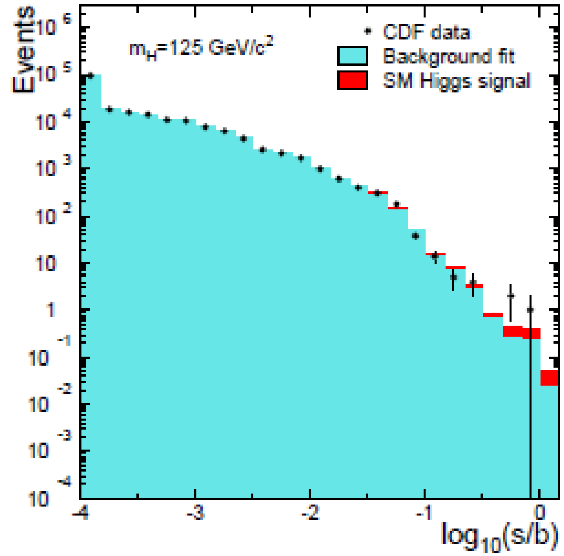
- **Utilize Multivariate Algorithms (MVA) for better S/B separation.**
  - Neural Net, Boosted Decision Tree, Matrix Element, etc.
  - Training of multiple MVAs in many channels.
- **Maximize trigger efficiency of each analysis.**
  - Analysis of events through different triggers.
- **Improved *b*-jet energy scale measurement** (low mass analyses)
  - *b*-jet energy correction based on NN at CDF.
- **Improved b-tagging** (low mass analyses)
  - Algorithms based on MVA.
- **Divide analysis sample into high/low purity subsamples.**
  - Subdivision due to lepton and *b*-tag quality.

2013 Collected Event Distribution

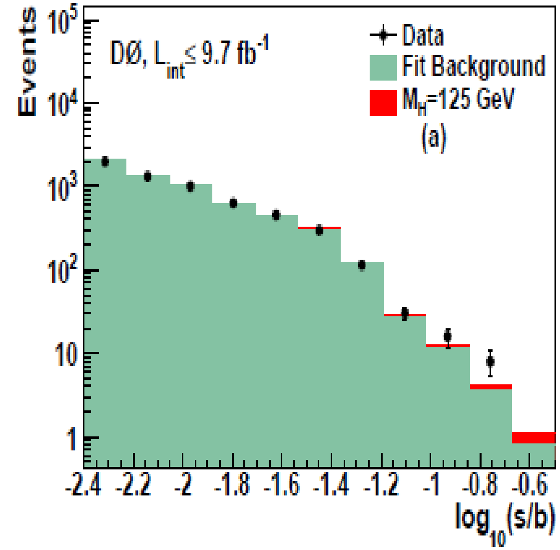
Tevatron

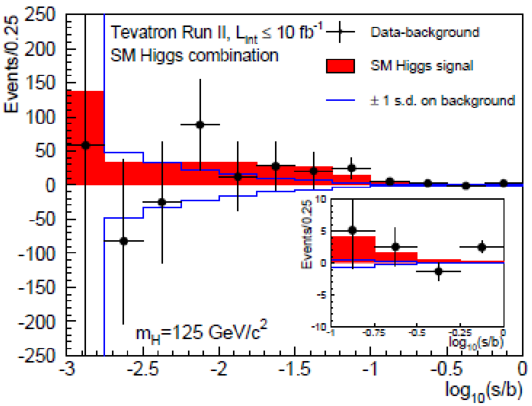


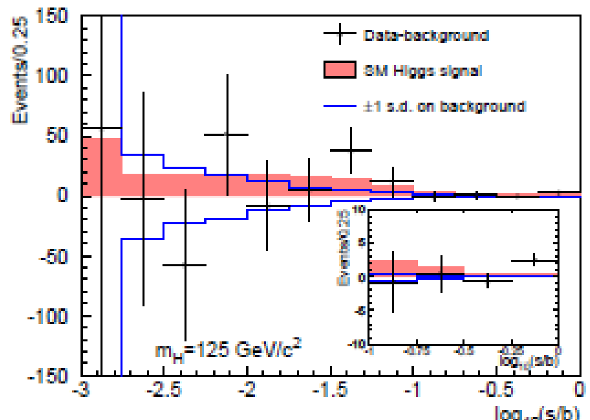
CDF

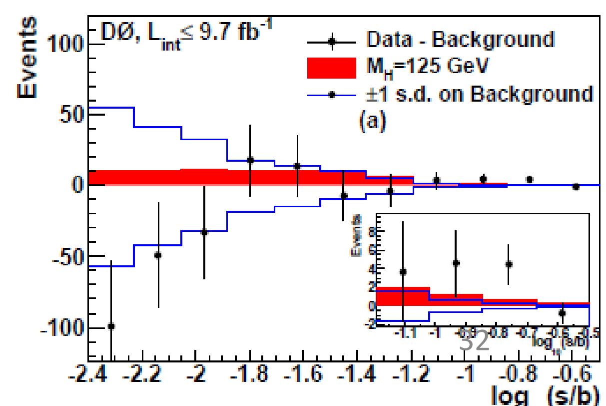


D0

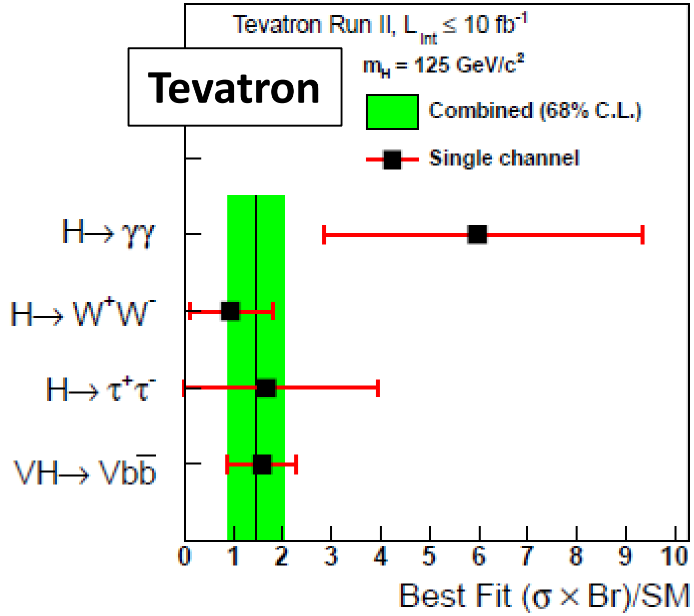


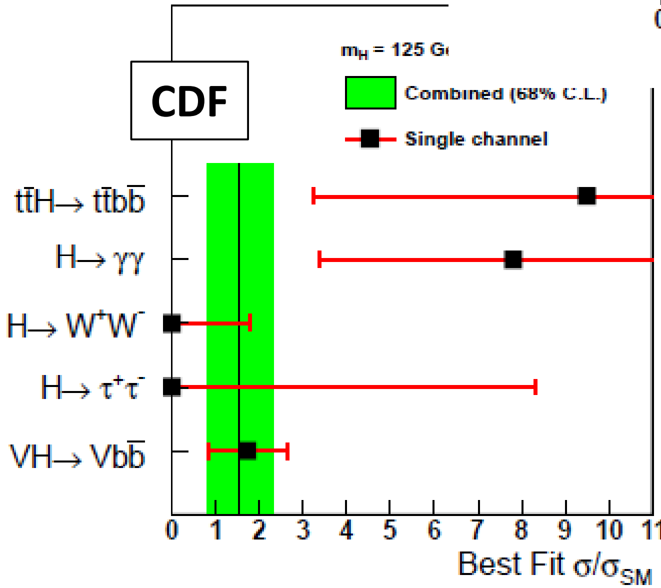


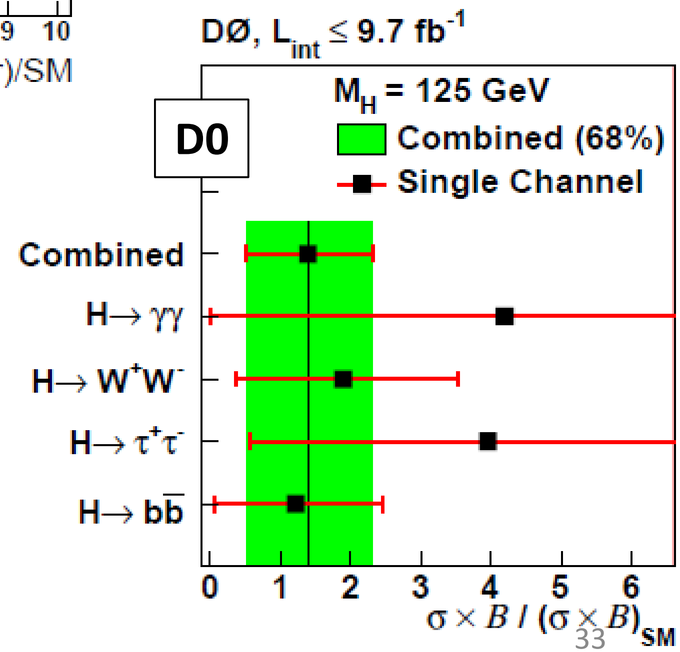




2013 Best Fit $\sigma_H \cdot Br/SM$

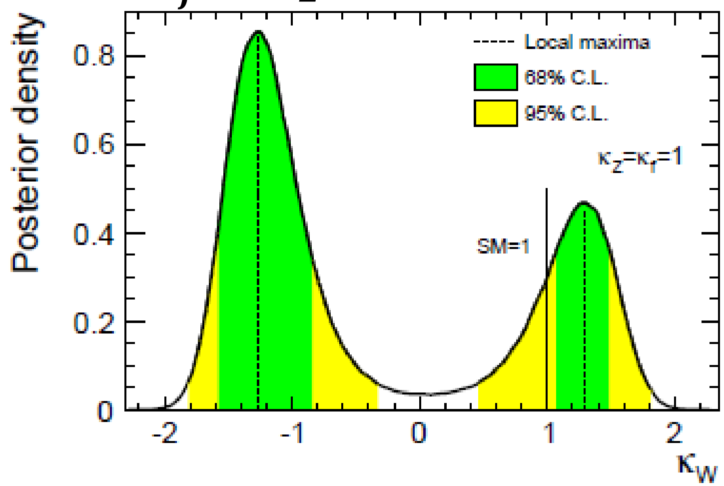




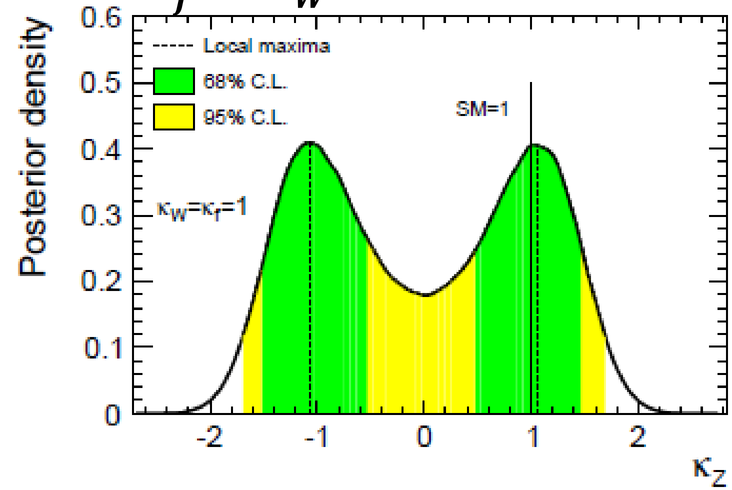


HWW, *HZZ* and *Hff* Couplings

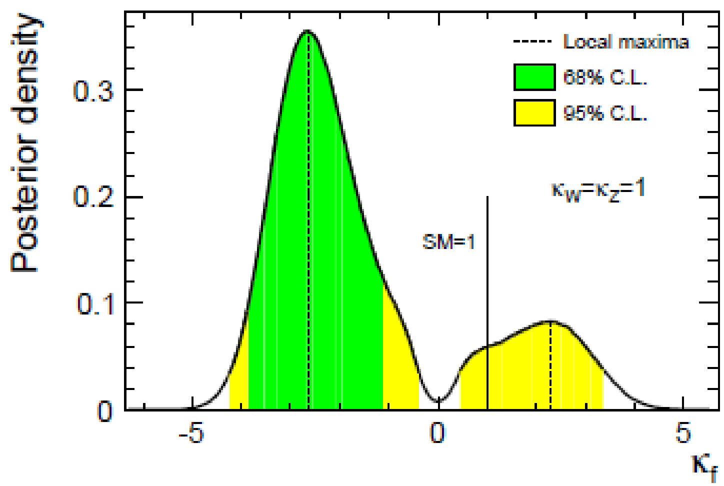
$\boldsymbol{K_f = K_Z = 1}$



$\boldsymbol{K_f = K_W = 1}$



$\boldsymbol{K_W = K_Z = 1}$



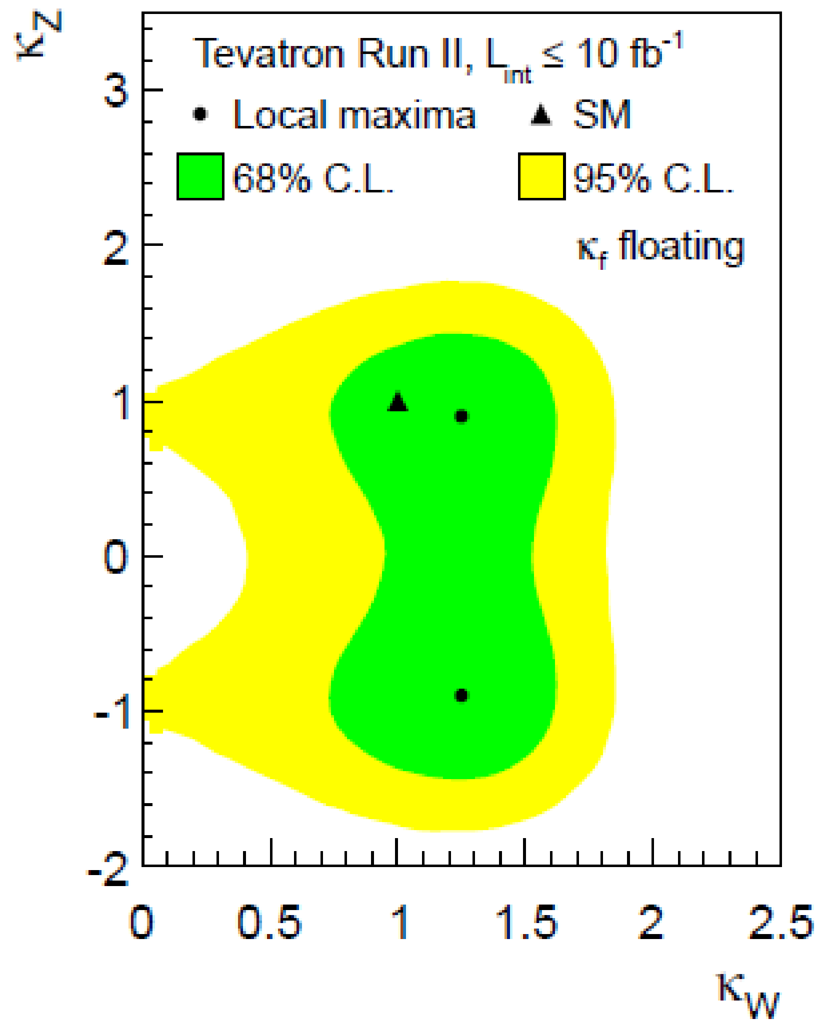
$$\boldsymbol{K_W = -1.27^{+0.46}_{-0.29}}, \textbf{ or } \boldsymbol{1.04 < K_W < 1.51}$$
$$\boldsymbol{K_Z = \pm(1.05^{+0.45}_{-0.55})}$$
$$\boldsymbol{K_f = -2.64^{+1.59}_{-1.30}}$$

Negative values preferred for K_W and K_f due to $H \to \gamma\gamma$ excess.

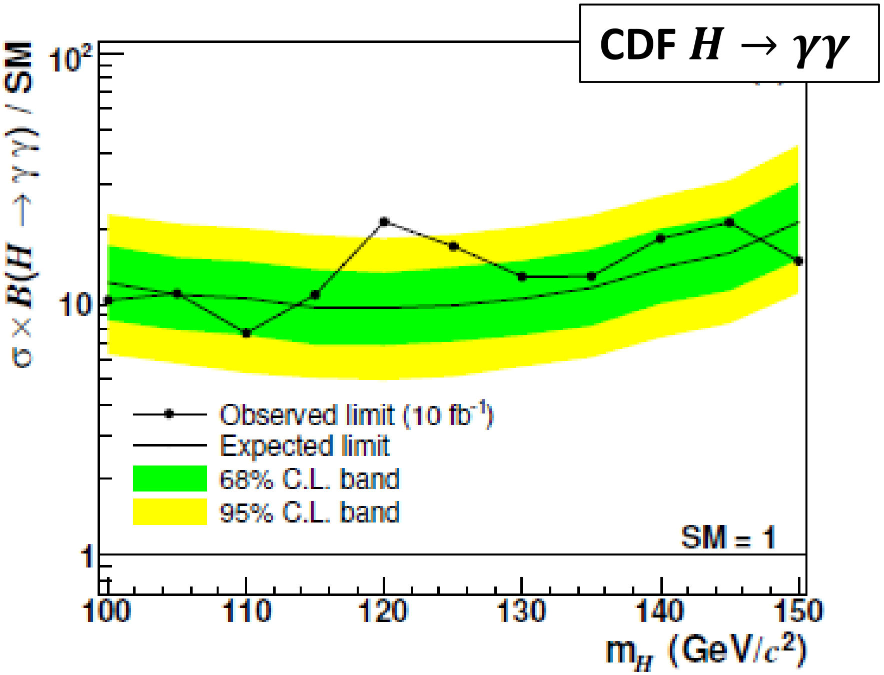
HWW and HZZ Couplings

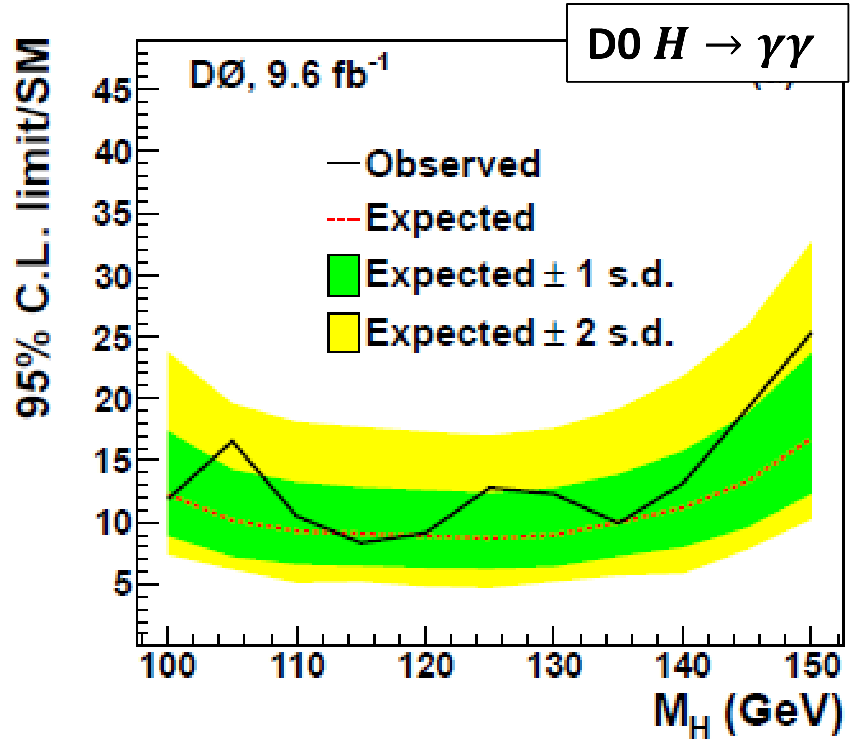
- K_f floating.

- Result is consistent with SM.
- Preferred region around:
  $(K_W, K_Z) = (1.25, \pm 0.90)$

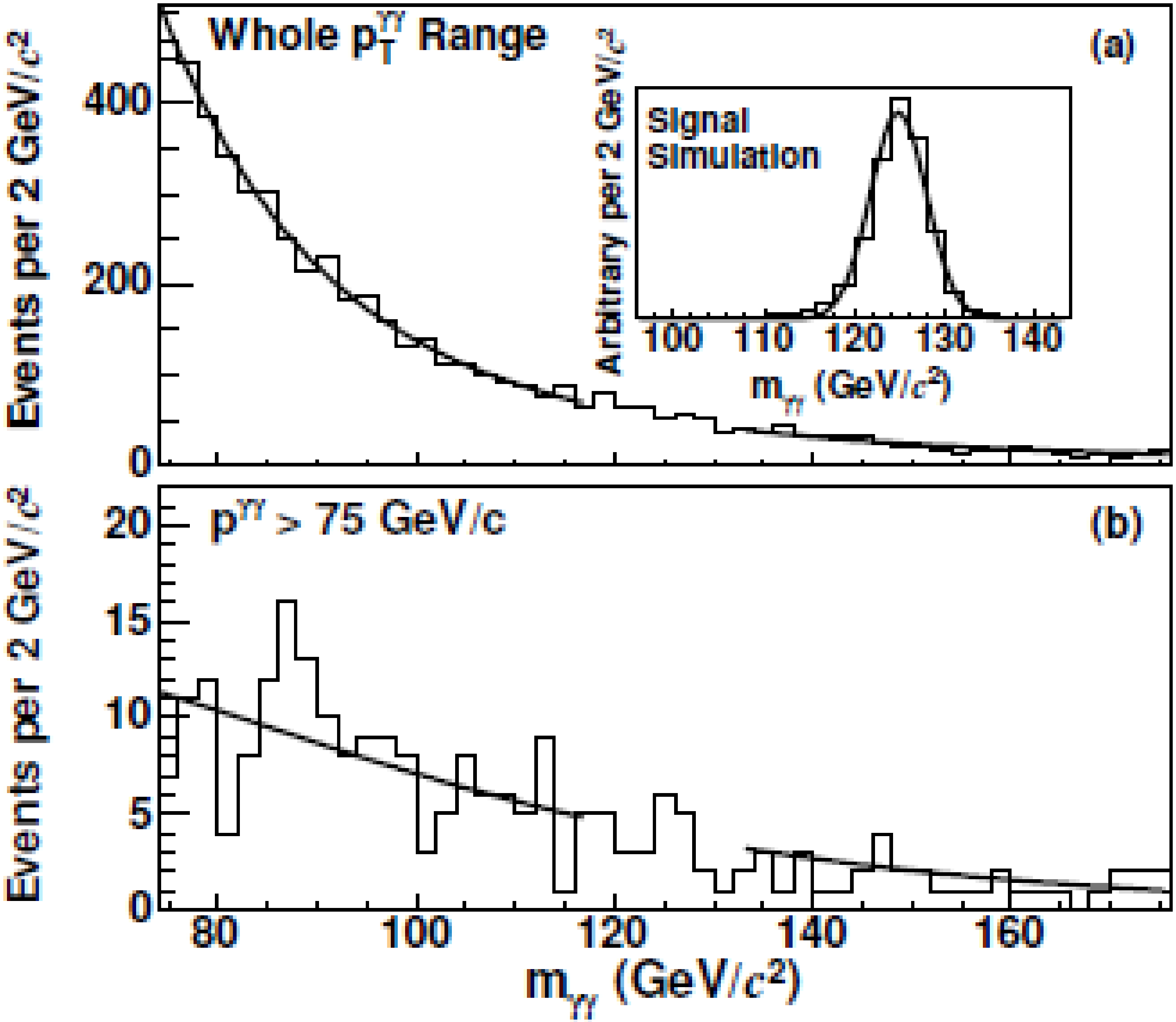


$H \to \gamma\gamma$ Limits by Experiment



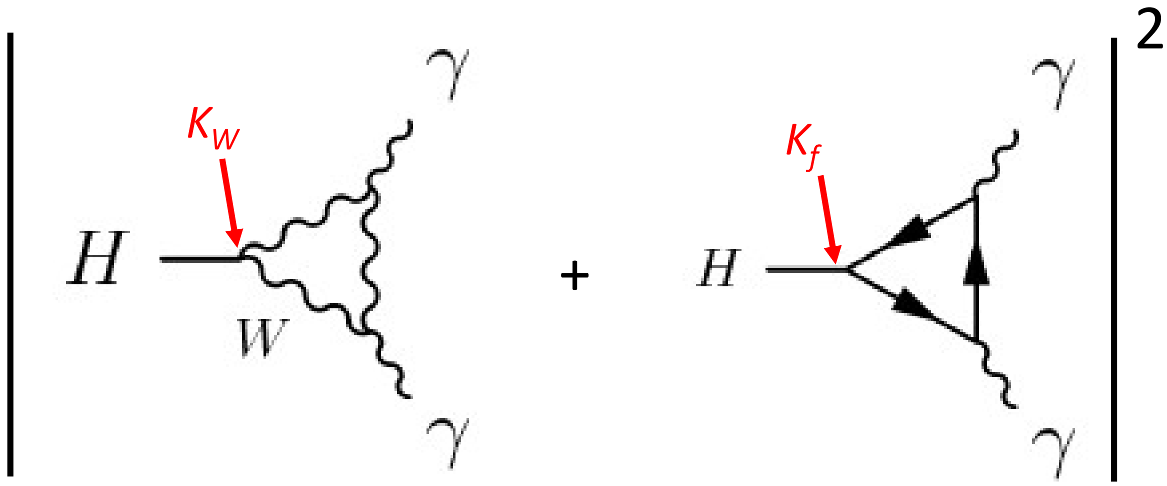


CDF H->γγ



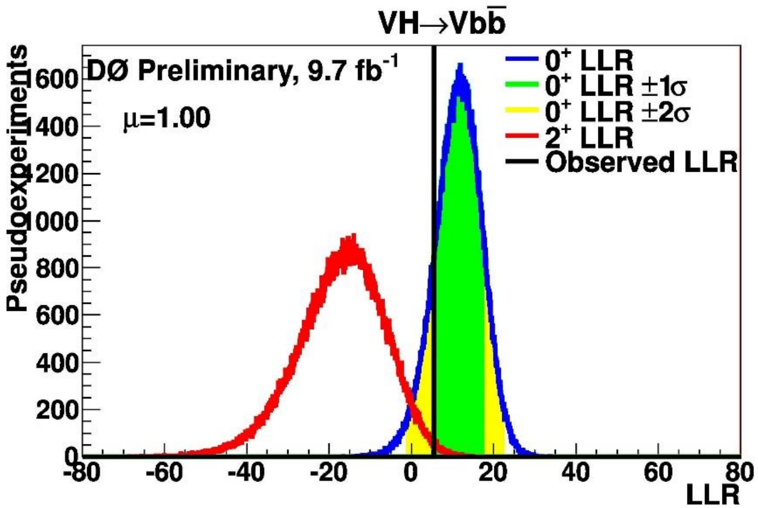
Whole $p_T^{\gamma\gamma}$ Range
(a)
Events per 2 GeV/c^2
400
200
0
Signal
Simulation
Arbitrary per 2 GeV/c^2
100
110
120
130
140
$m_{\gamma\gamma}$ (GeV/c^2)
$p^{\gamma\gamma}$ > 75 GeV/c
(b)
20
15
10
5
0
80
100
120
140
160
$m_{\gamma\gamma}$ (GeV/c^2)

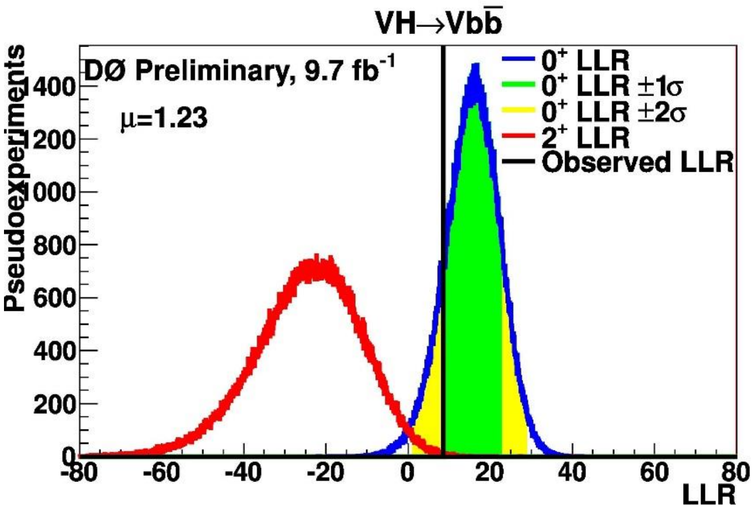
Coupling Factor for $H \to \gamma\gamma$



$$\Gamma(H \to \gamma\gamma) = \Gamma(H \to \gamma\gamma)_{SM} \times |1.28\ \kappa_V - 0.21\ \kappa_f|^2$$

D0 Spin and Parity Measurement 2





Channel	$WH \to \ell\nu b\bar{b}$	$ZH \to \ell\ell b\bar{b}$	$ZH \to \nu\nu b\bar{b}$	Combined
	$J^P = 2^+$ vs. $J^P = 0^+$			
CL_{2+} Exp. ($\mu = 1.00$)	0.015	0.080	0.035	0.0004
CL_{0+} Exp. ($\mu = 1.00$)	0.5	0.5	0.5	0.5
CL_{2+} Obs. ($\mu = 1.00$)	0.153	0.154	0.017	0.007
CL_{0+} Obs. ($\mu = 1.00$)	0.847	0.693	0.359	0.849
1-CL_s Exp. ($\mu = 1.00$)	0.946	0.840	0.926	0.9995
1-CL_s Obs. ($\mu = 1.00$)	0.831	0.778	0.948	0.992
CL_{2+} Exp. ($\mu = 1.23$)	0.005	0.052	0.021	6×10^{-5}
CL_{0+} Exp. ($\mu = 1.23$)	0.5	0.5	0.5	0.5
CL_{2+} Obs. ($\mu = 1.23$)	0.013	0.097	0.008	0.001
CL_{0+} Obs. ($\mu = 1.23$)	0.903	0.675	0.346	0.855
1-CL_s Exp.($\mu = 1.23$)	0.975	0.897	0.958	0.9999
1-CL_s Obs.($\mu = 1.23$)	0.893	0.857	0.976	0.999