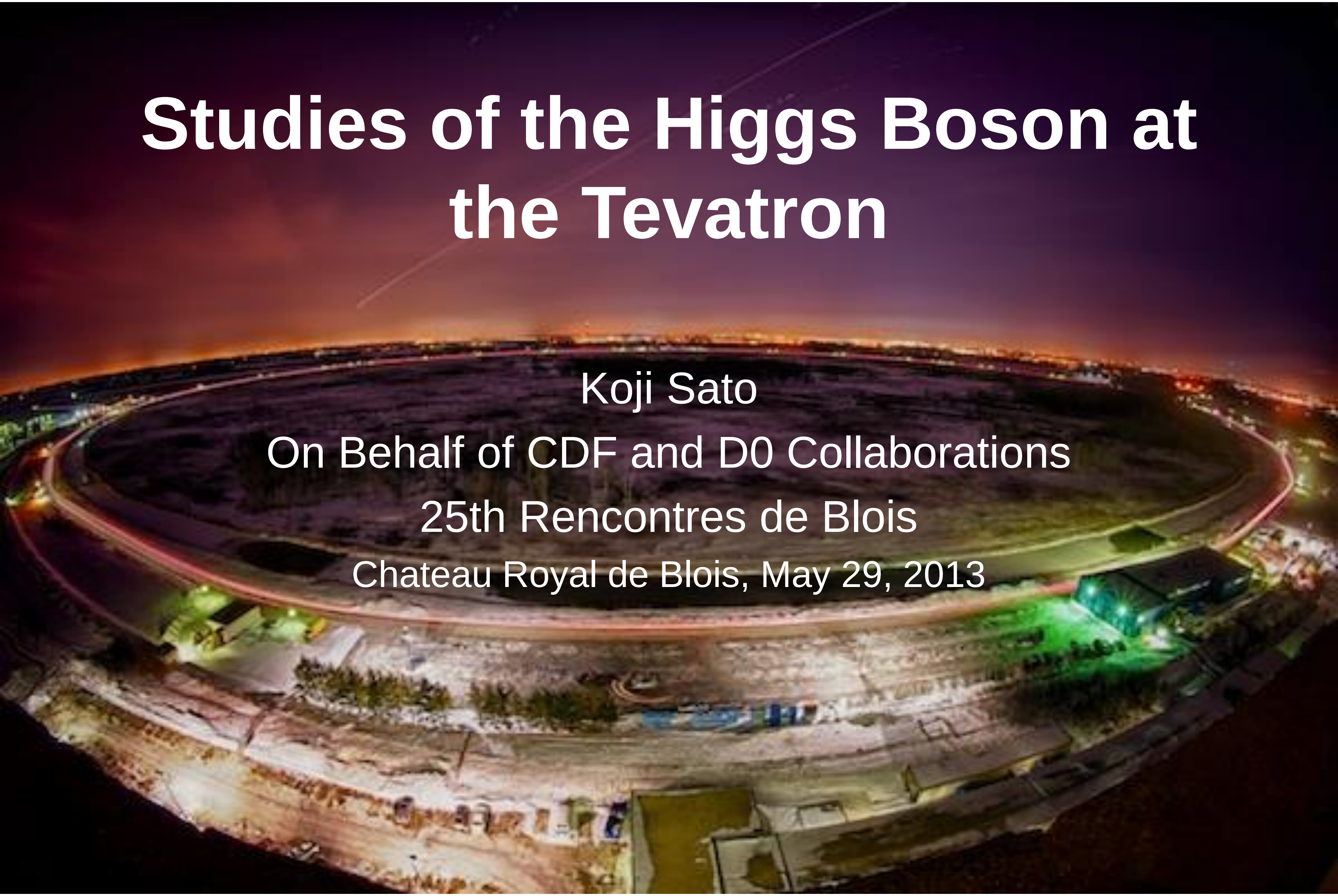


Studies of the Higgs Boson at the Tevatron

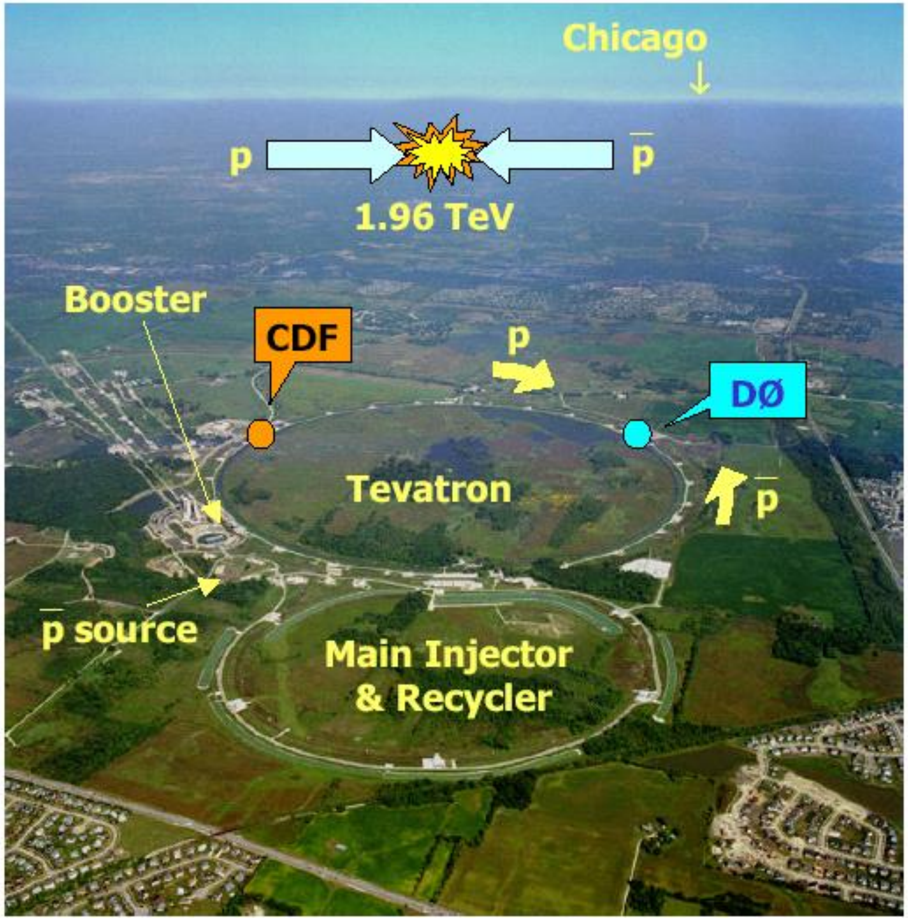
Koji Sato

On Behalf of CDF and D0 Collaborations

25th Rencontres de Blois

Chateau Royal de Blois, May 29, 2013

Tevatron Run II

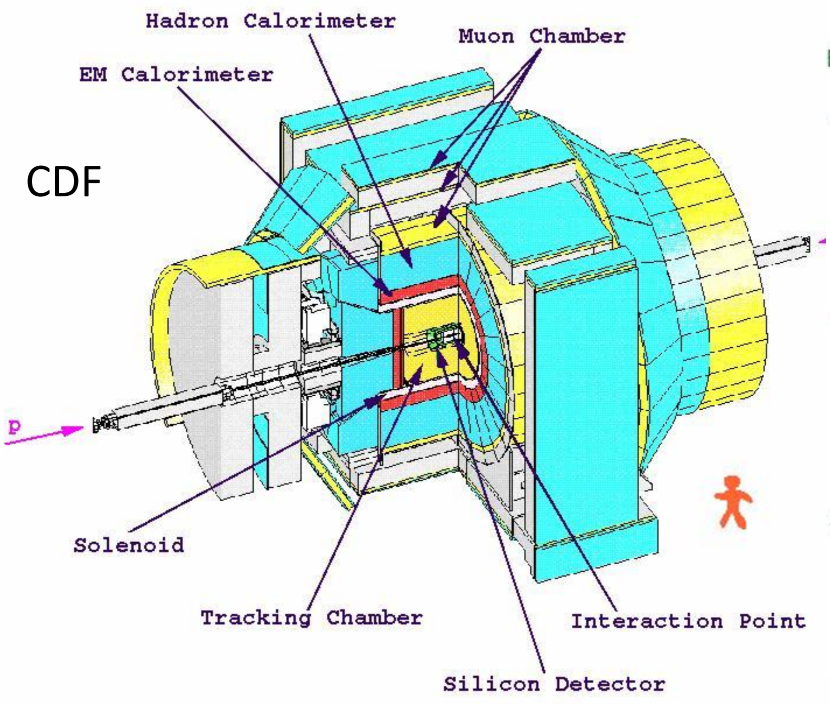


- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV (1.8 TeV in Run I).
- Run II:
  Summer 2001 - Autumn 2011.
- Collisions at world highest energy until Nov 2009.
  - Energy frontier for ～25 years!!
- Two detectors (CDF and D0) for wide range of physics studies.
- Delivered: 12 fb^{-1}.
  - Recorded by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

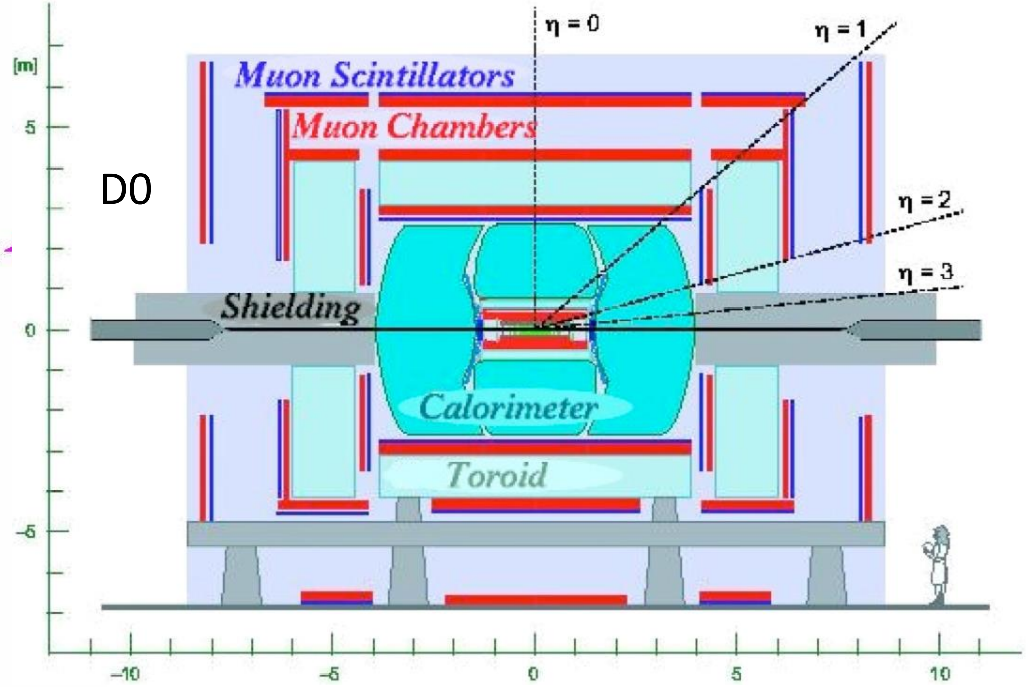
CDF and D0 Detectors

- 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 :

  $m_W = 80.426 \pm 0.034$ GeV/c^2

  With Tevatron Run II results :

  $m_W = 80.385 \pm 0.015$ GeV/c^2

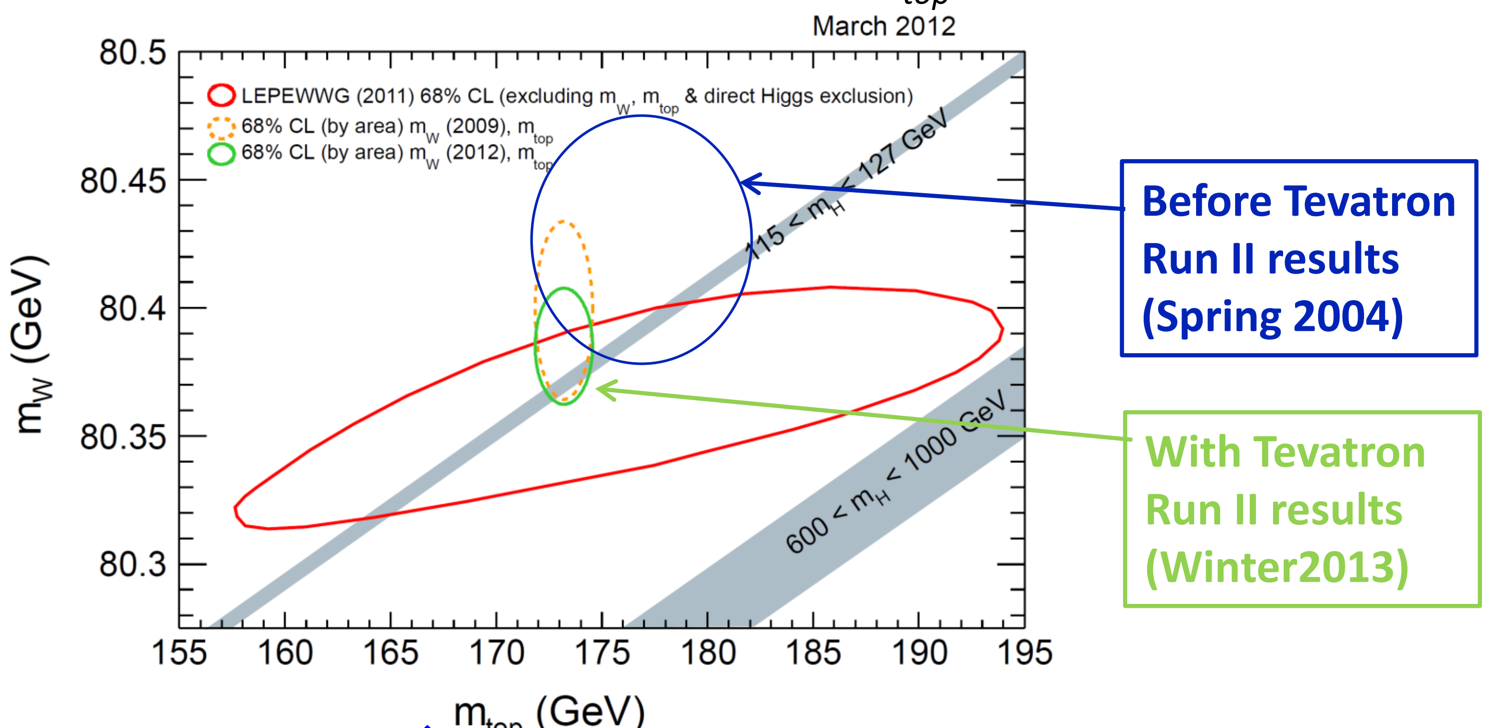
- Mass of Top Quark (World Average):

  Tevatron Run I result :

  $m_{top} = 178.0 \pm 4.3$ GeV/c^2

  With Tevatron Run II results :

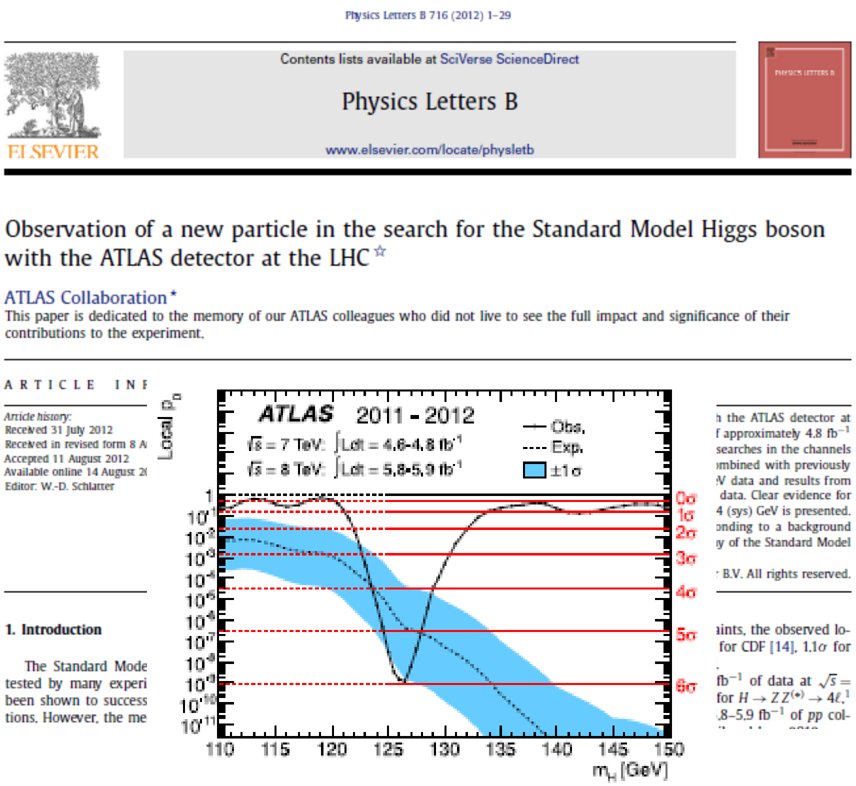
  $m_{top} = 173.2 \pm 0.9$ GeV/c^2



$M_{higgs} < 152$ 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

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Physics Letters B

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ELSEVIER

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.

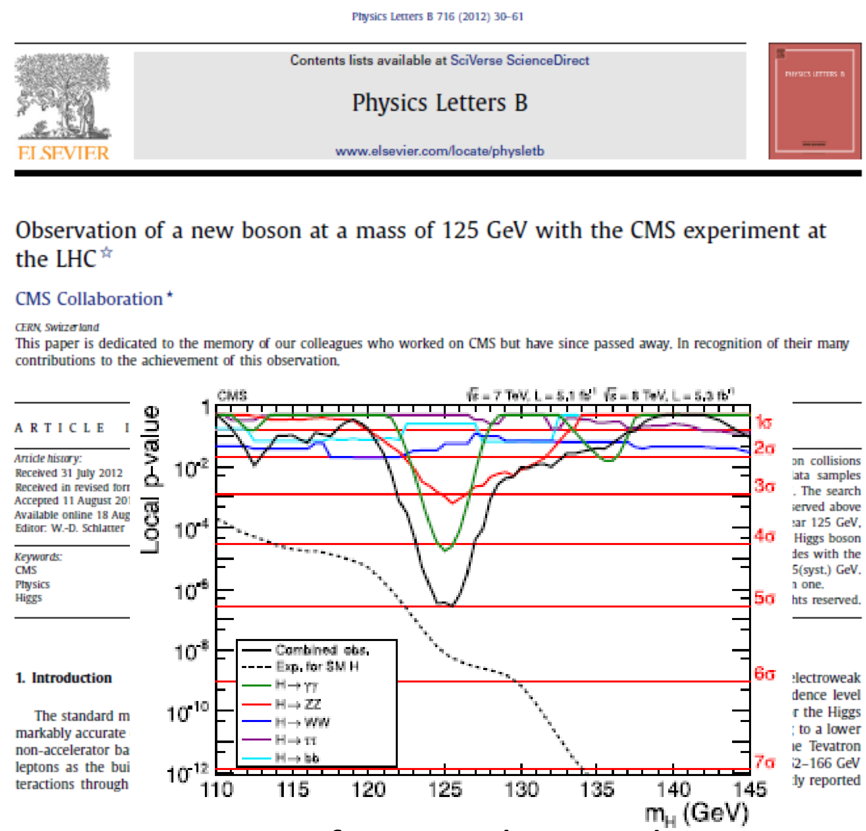
ARTICLE INFO

Article history:
Received 31 July 2012
Accepted 11 August 2012
Editor: W.-D. Schlatter

1. Introduction

The Standard Mode tested by many experi been shown to success tions. However, the me

ATLAS: 5.9 σ from Background


Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

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.

ARTICLE INFO

Article history:
Received 31 July 2012
Keywords:
CMS
Physics
Higgs

1. Introduction

The standard m markably accurate non-accelerator ba leptons as the bui teractions through

CMS: 5.0 σ from Background

Discovery was driven by $H \to \gamma\gamma$, 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

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A. Anastassov,[76,*,c] A. Annovi,[34,*] J. Antos,[53,*] G. Apollin
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S. Banerjee,[31,†] A. Barbaro-Galtieri,[68,*] E. Barberis,[92,
P. Barria,[36c,36a,*] J. F. Bartlett,[76,†] P. Bartos,[53,*] U. Bassle
F. Bedeschi,[36a,*] M. Begalli,[2,†] S. Behari,[90,*] L. Bellantoni,[76,
A. Beretvas,[76,*] S. B. Beri,[29,†] G. Bernardi,[17,†] R. Bernhard
P. C. Bhat,[76,†] S. Bhatia,[99,†] V. Bhatnagar,[29,†] A. Bhatti,[10
K. R. Bland,[122,*] G. Blazey,[79,†] S. Blessing,[74,†] K. Bloom,
A. Boehnlein,[76,†] D. Boline,[107,†] E. E. Boos,[50,†] G. Boriss
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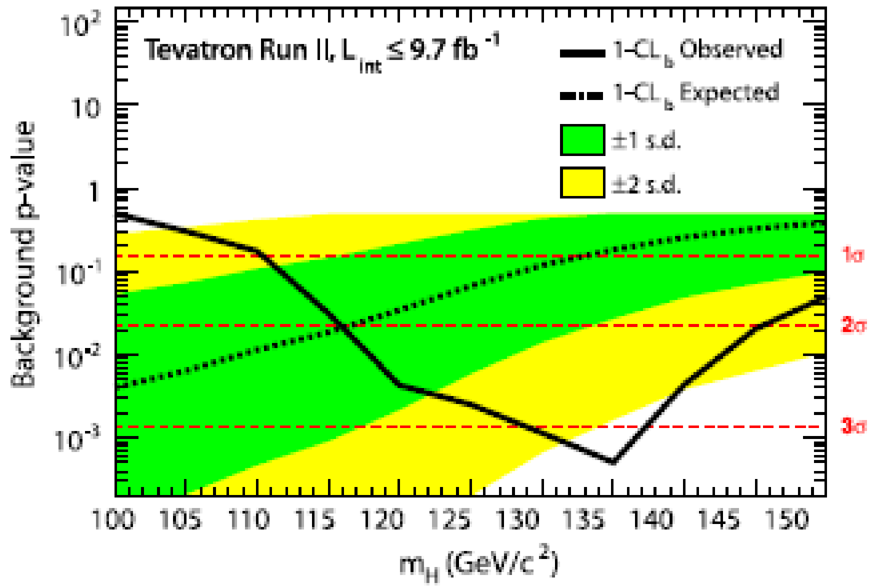
A. Buzatu,[4,*]
I. Campb
M. C
D. Cauz,
Chakrabor



TEVATRON Summer 2012:

Excess at $m_H = 120 - 135$ GeV/c² mass region.

3.1 σ from Background in Combination of searches for $H \rightarrow bb$ analyses.

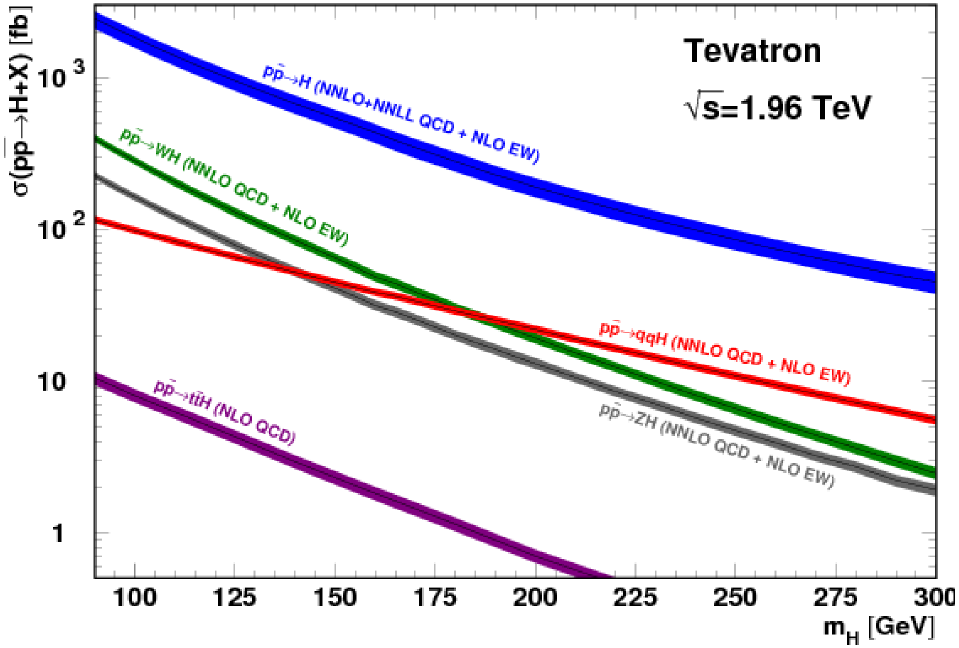
Complementary to LHC results

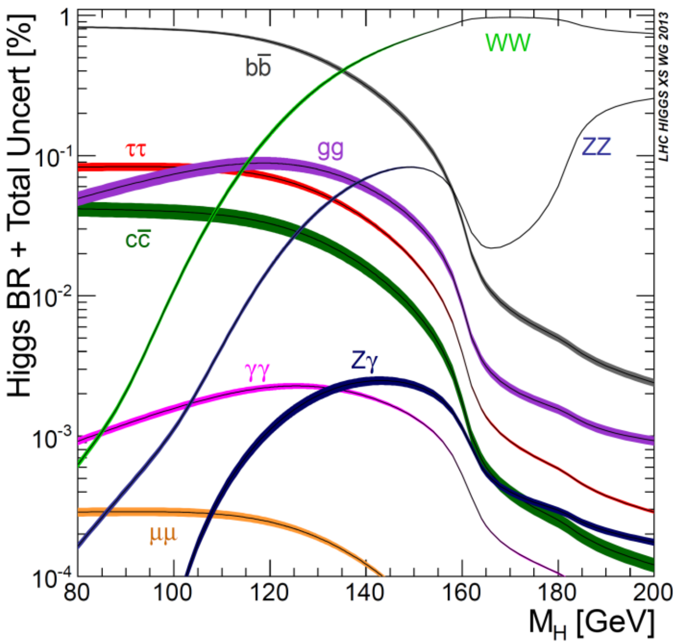
Discovery was driven by $H \rightarrow \gamma\gamma$, ZZ and WW decay modes.

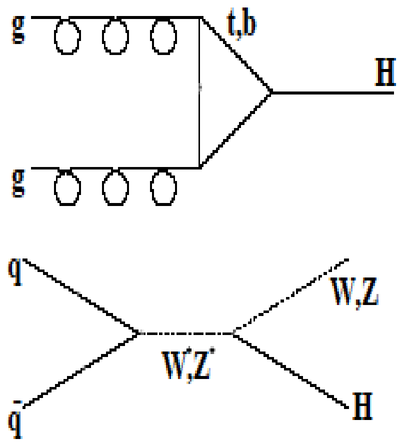
Tevatron Winter 2013 Combination

- Although we know $m_H \sim 125\ \mathrm{GeV}/c^2$ from LHC results, we present our analyses over full mass range.
- Analysis updates in a few channels since last Summer.
- Studies of Higgs couplings to Fermions and Bosons.

SM Higgs Production and Decay at Tevatron







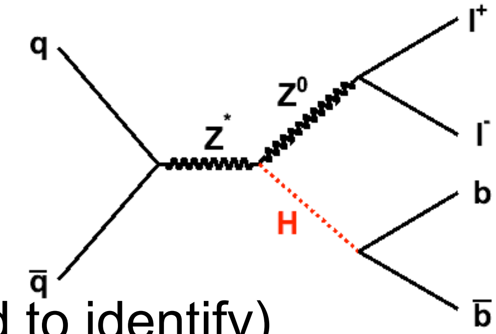
Channels with best sensitivity are:

- 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.

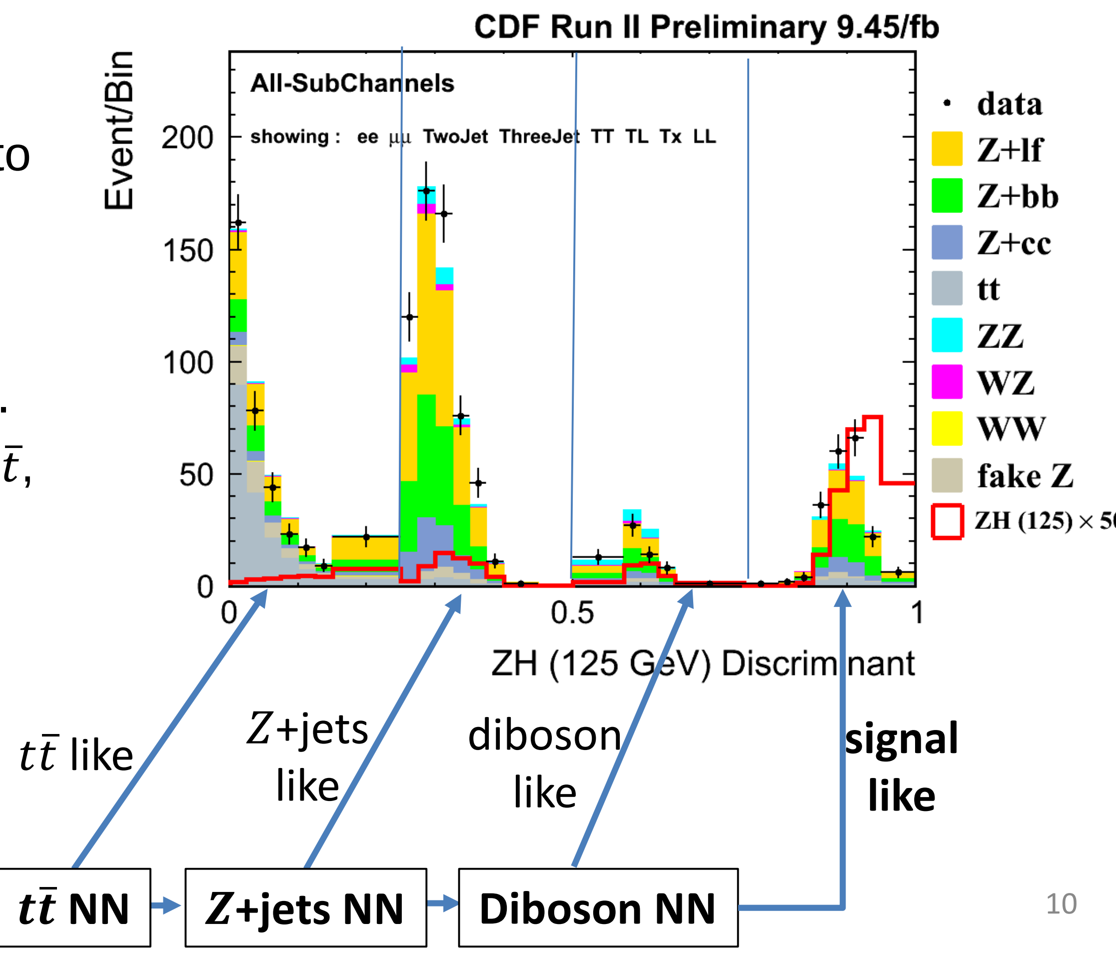
CDF and D0 analyses

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

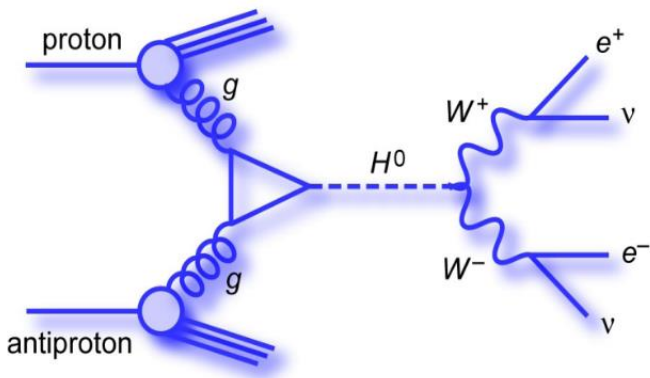
CDF: $ZH \rightarrow llbb$ Analysis



- 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.

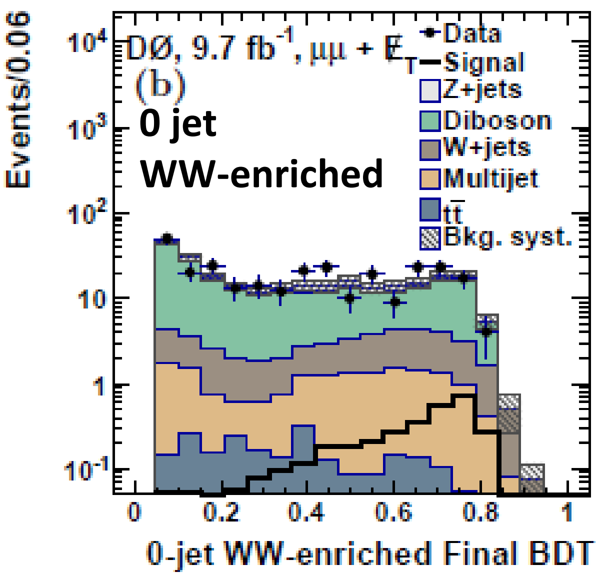


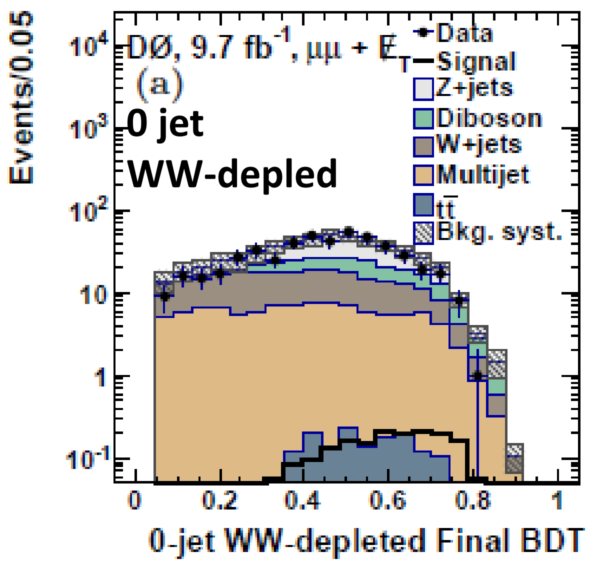
D0: $H \to W^+W^- \to l^+l^- + MET$ Channel

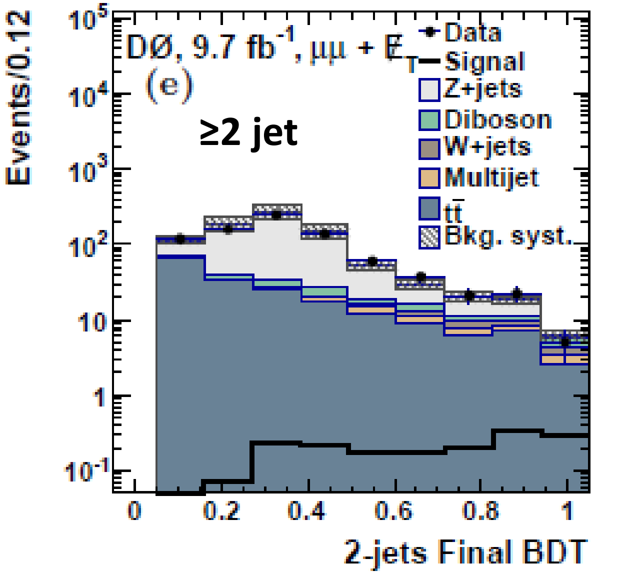


- e^+e^-, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ pair within $M_{ll} > 15$ GeV.
- BDT to reject $Z/\gamma^* \to ll$ in e^+e^-, $\mu^+\mu^-$ events.
- $gg \to H, WH, ZH, VBF$ are considered as signal.
  - Events with different jet multiplicity have different s/b composition.
  - Separately analyze 0, 1, ≥2 jet 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 $\mu\mu$ channel):







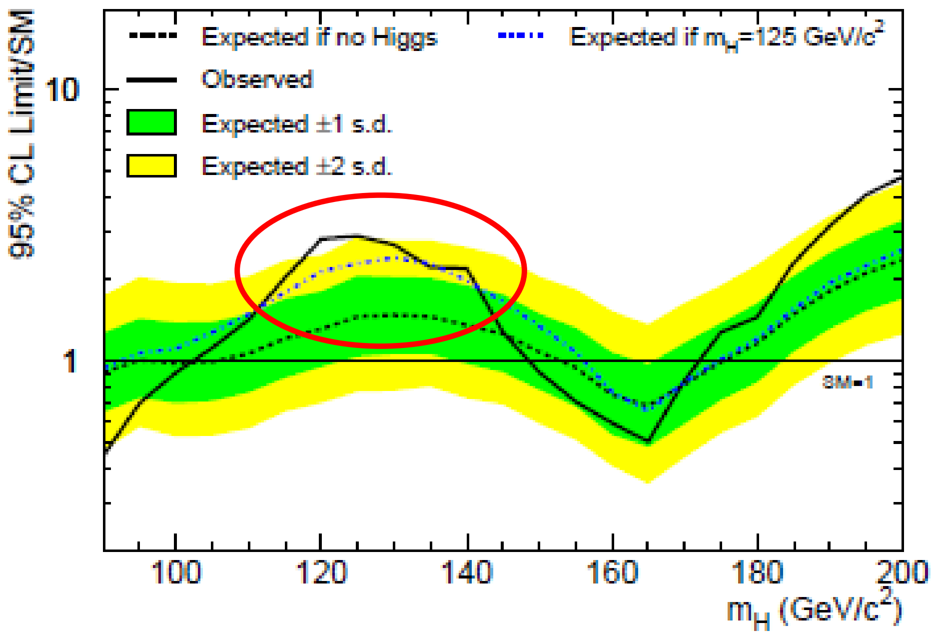
General Strategy for Improved Sensitivity

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

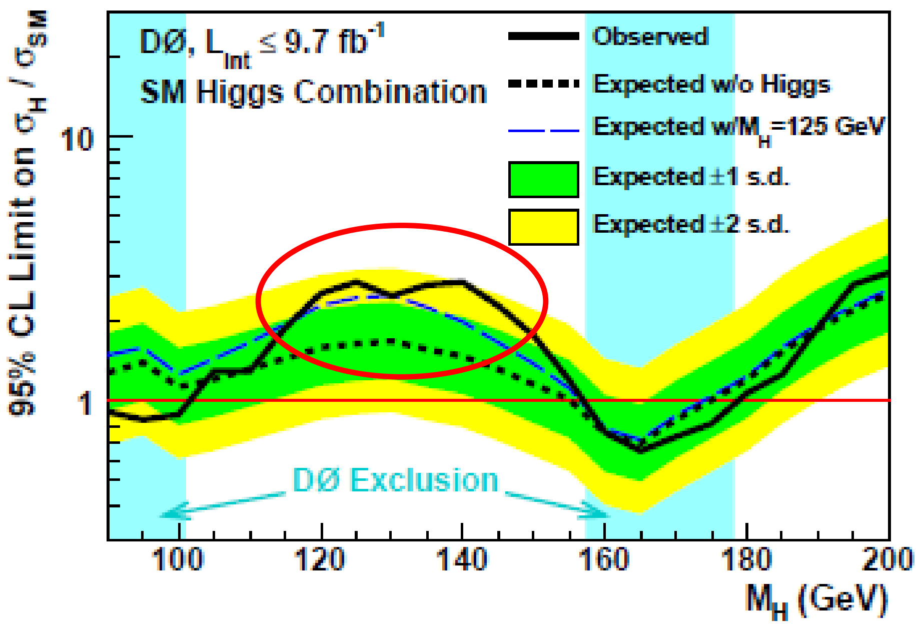
- **Utilize Multivariate Algorithms (MVA) for better S/B separation.**
  - Neural Net, Boosted Decision Tree, Matrix Element, etc.
  - Training of multiple MVAs in many channels.
- **Maximize trigger efficiency of each analysis.**
  - Analysis of events through different triggers.
- **Improved *b*-jet 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.

CDF and D0: Combined Limit

CDF



D0



CDF excludes (95% C.L.):

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

$149 < m_H < 172$ 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.):

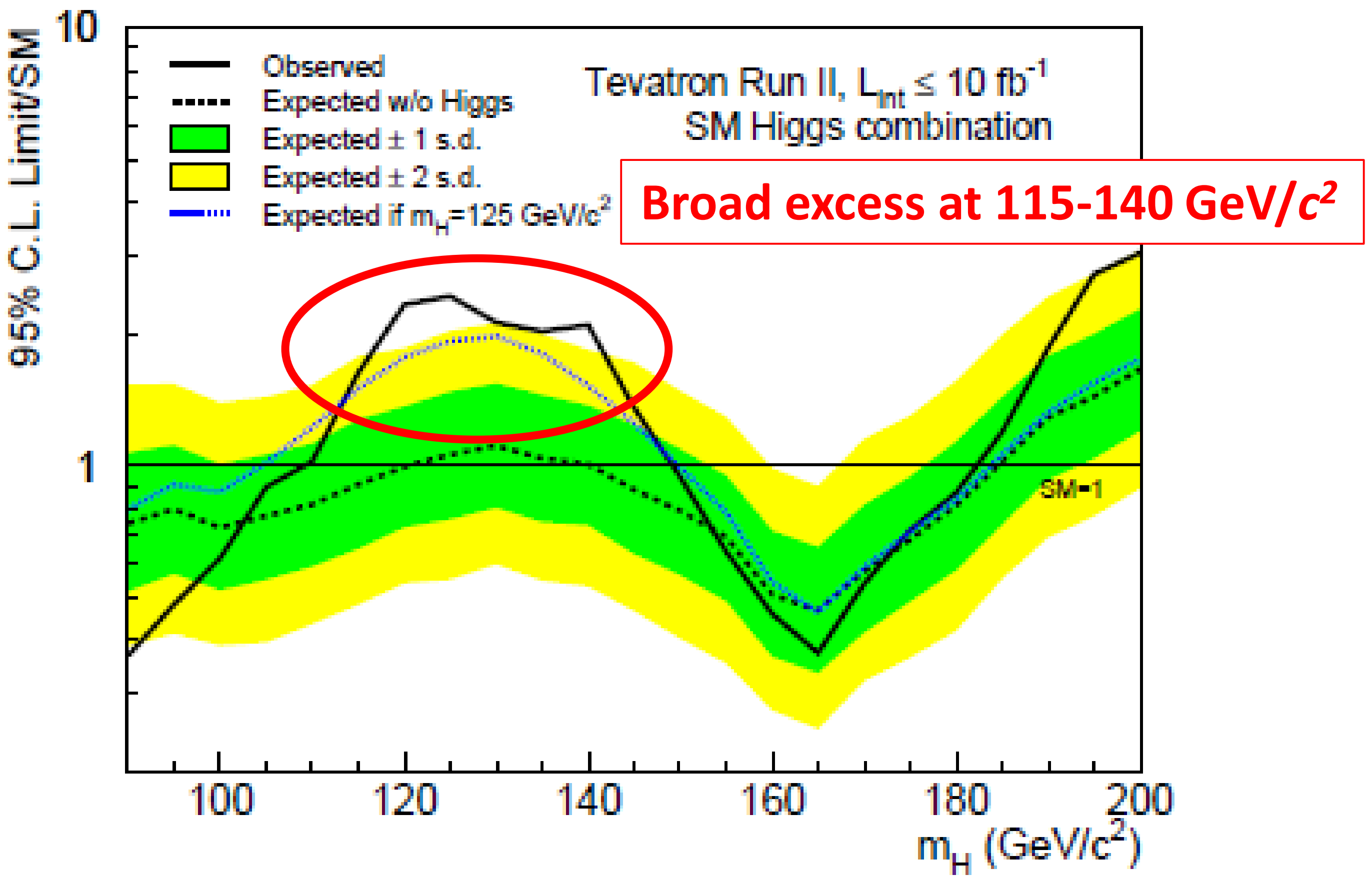
$90 < m_H < 94$, $96 < m_H < 106$ GeV/c^2

$153 < m_H < 175$ 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

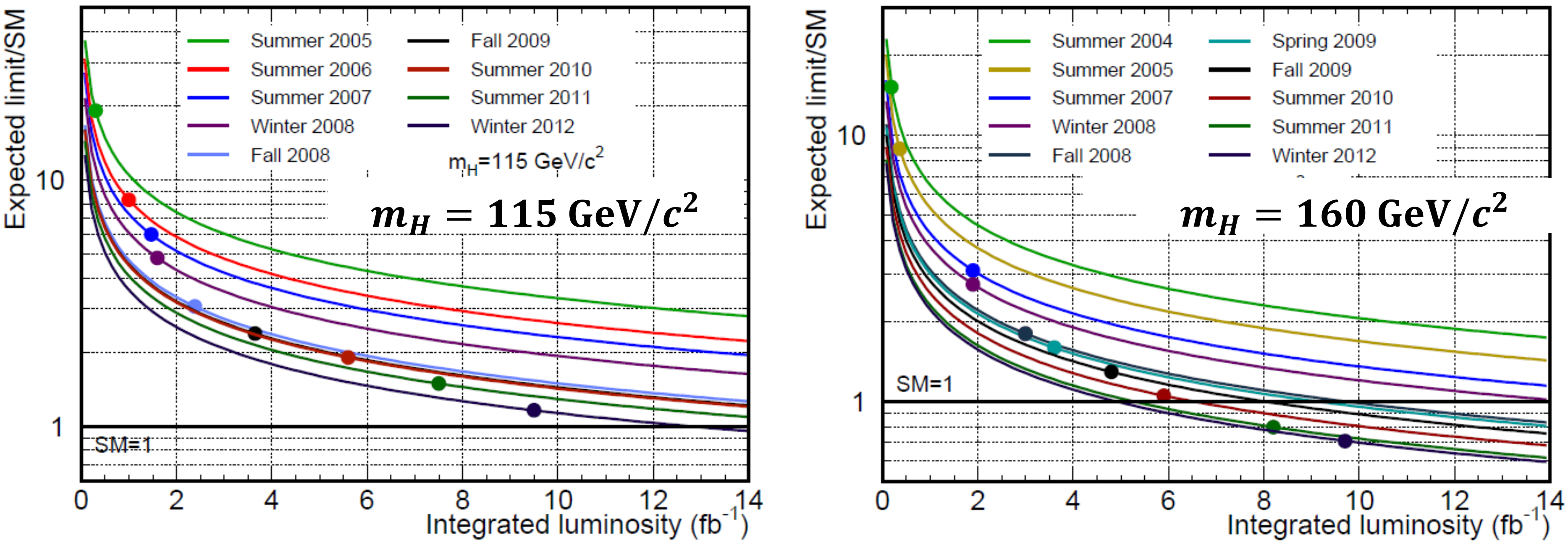
Expected exclusion:

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

History of Analysis Improvement

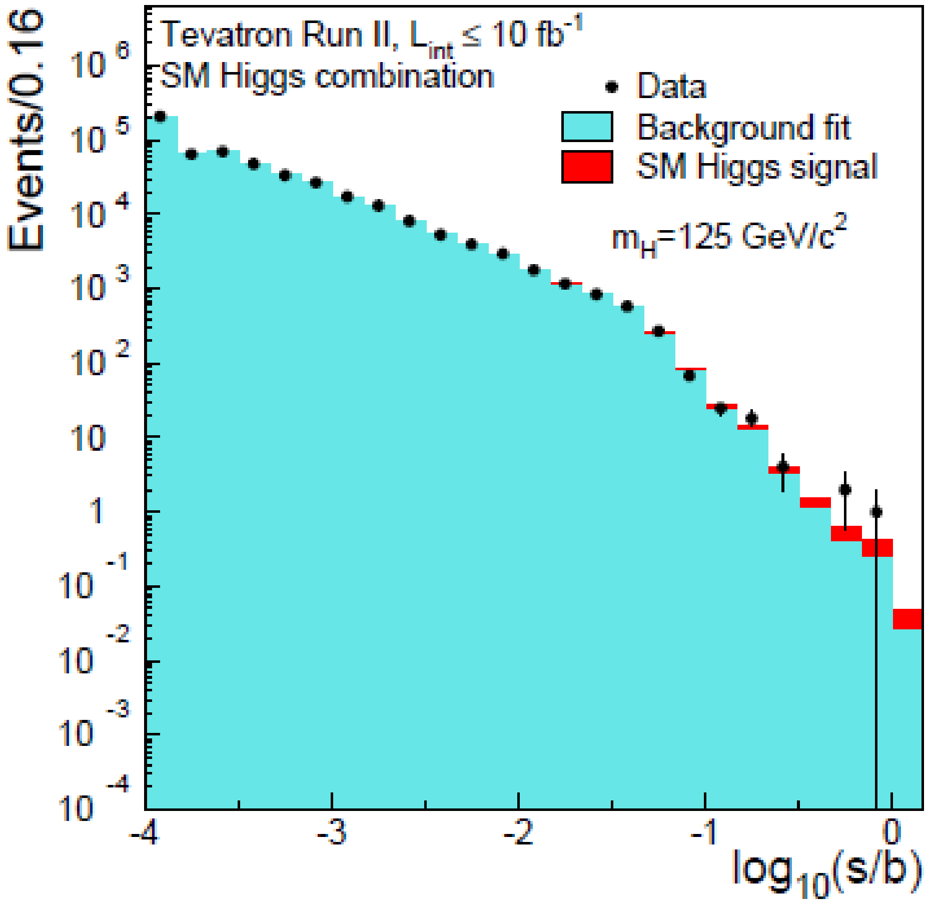
- Tevatron analyses have been constantly improved.
  - Improvement is far better than expected due to increase in data!!

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

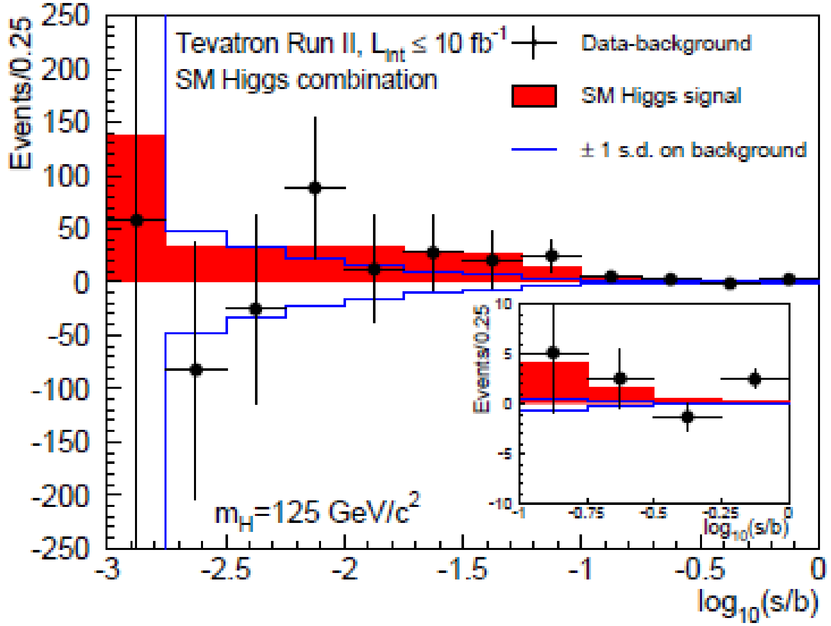


Distribution of the Candidate Events

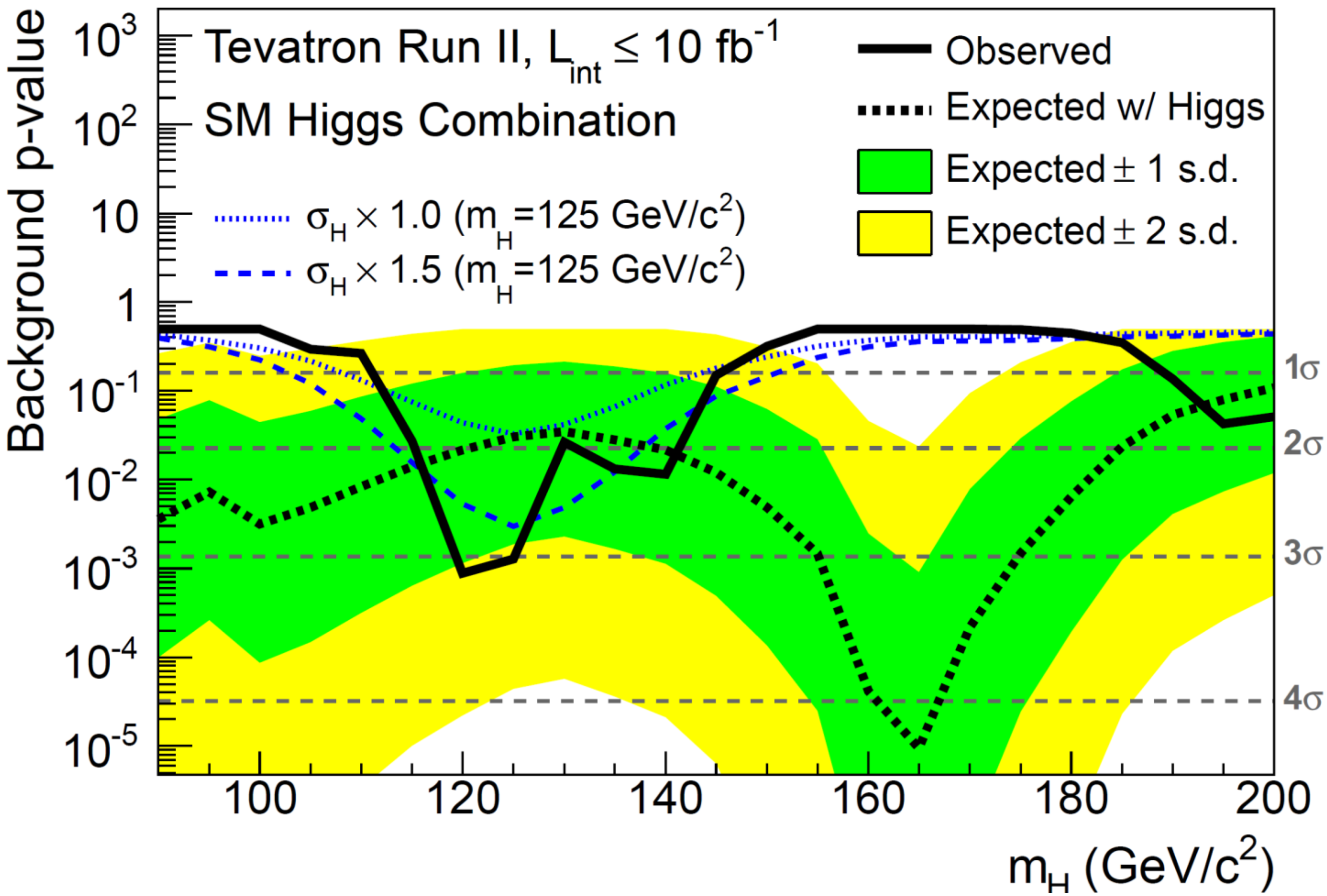
Candidate events in all the combined analyses:



Data - Background



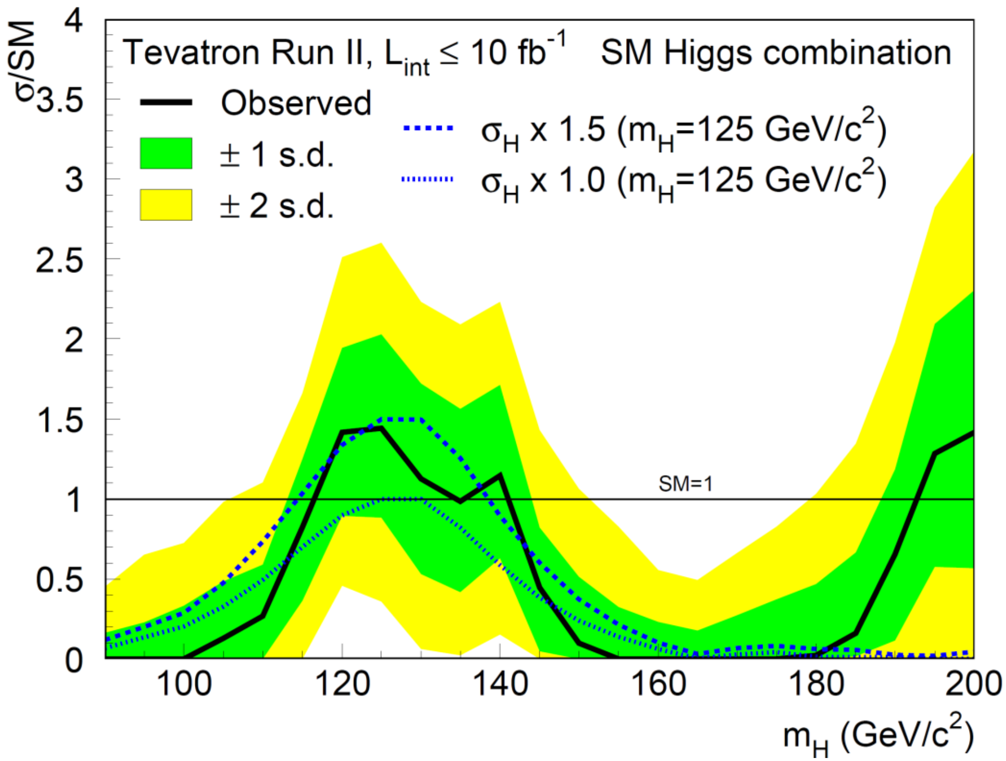
P-value of the Tevatron Combination



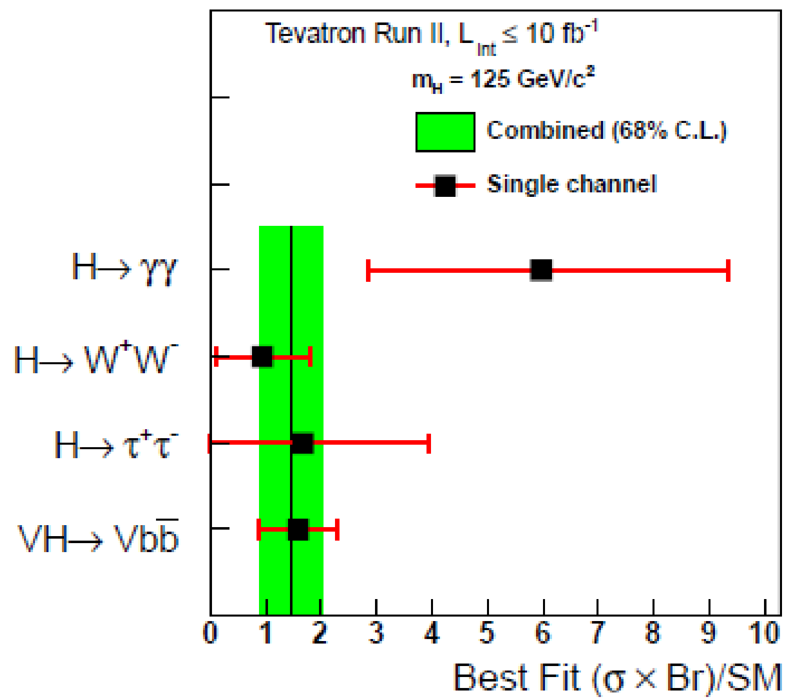
- 3.0 standard deviations at $m_H = 125\ \mathrm{GeV}/c^2$.

Signal Cross Section Best Fit

- Assuming the SM Higgs branching ratio:



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

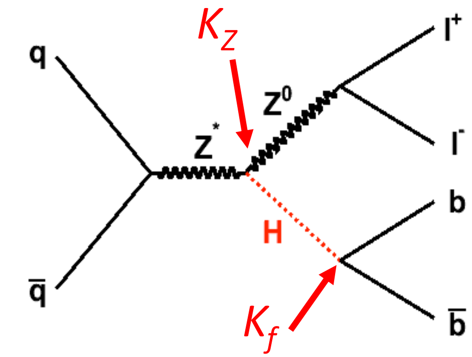


- $\frac{\sigma}{\mathrm{SM}} = 1.44^{+0.59}_{-0.56}$ for $m_H = 125\ \mathrm{GeV}/c^2$.
- Consistent across different decay modes.

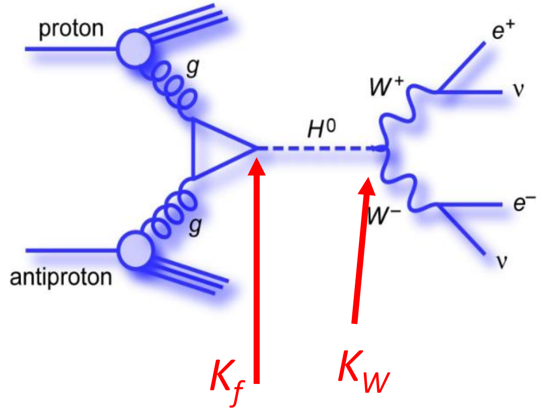
Studies of Higgs Couplings

- Coupling scale factor w.r.t. SM:
  - K_f: Fermion coupling *Hff*
  - K_W, K_Z, K_V: Boson couplings *HWW, HZZ, HVV*

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



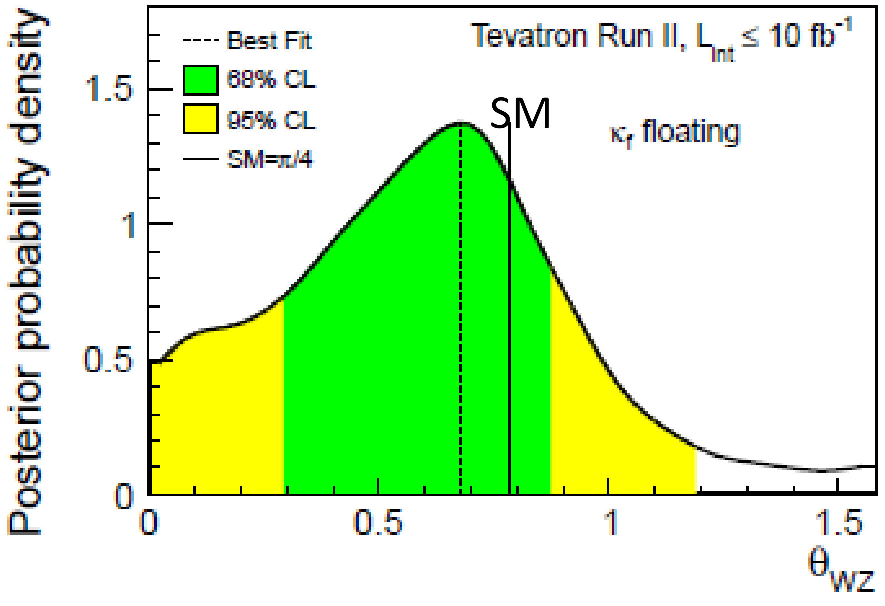
- Follow prescription of LHC Higgs working group arxiv:1209.0040.
- Assume a SM-like Higgs particle of 125 GeV.



Test of Custodial Symmetry

- K_f floating.
- Compute posterior probability density for

$$\theta_{WZ} = \tan^{-1}(K_Z/K_W).$$



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

$$\boldsymbol{K_W/K_Z = 1.24^{+2.32}_{-0.42}}$$

Constraint on *HVV* and *Hff* Couplings

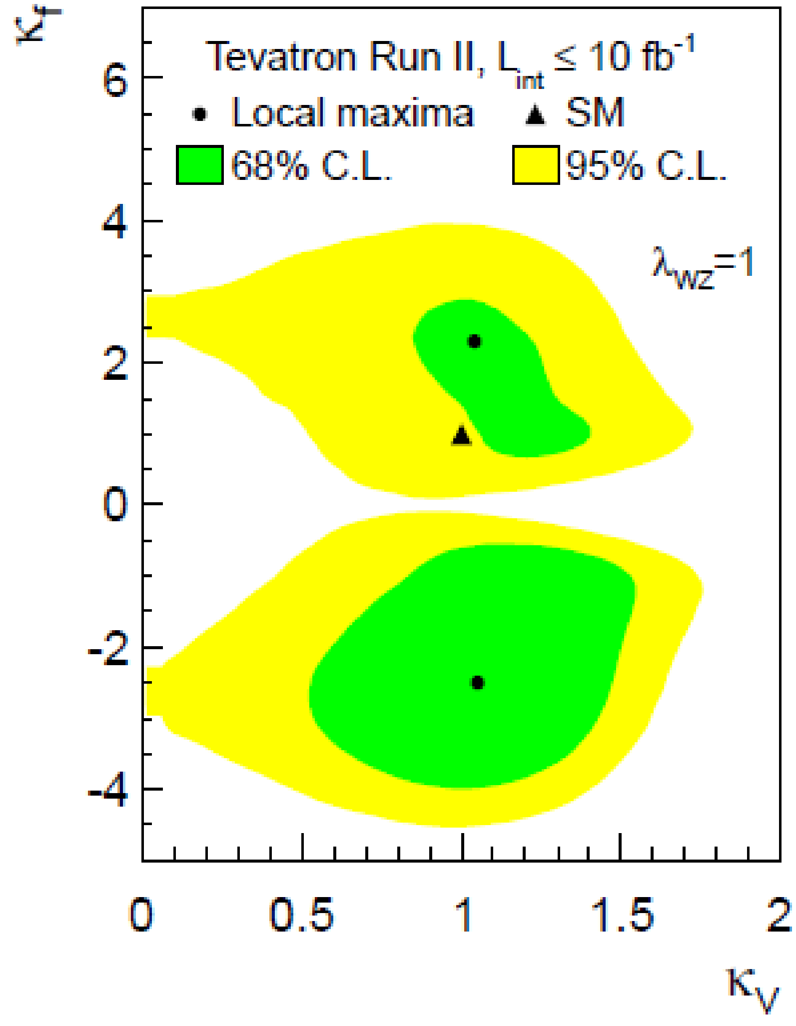
- Assuming:

  $K_W = K_Z \equiv K_V$

- Result is consistent with SM.
- Preferred regions around

  $$\left(K_V, K_f\right) = (1.05, -2.40), \quad (1.05, \ 2.30)$$

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

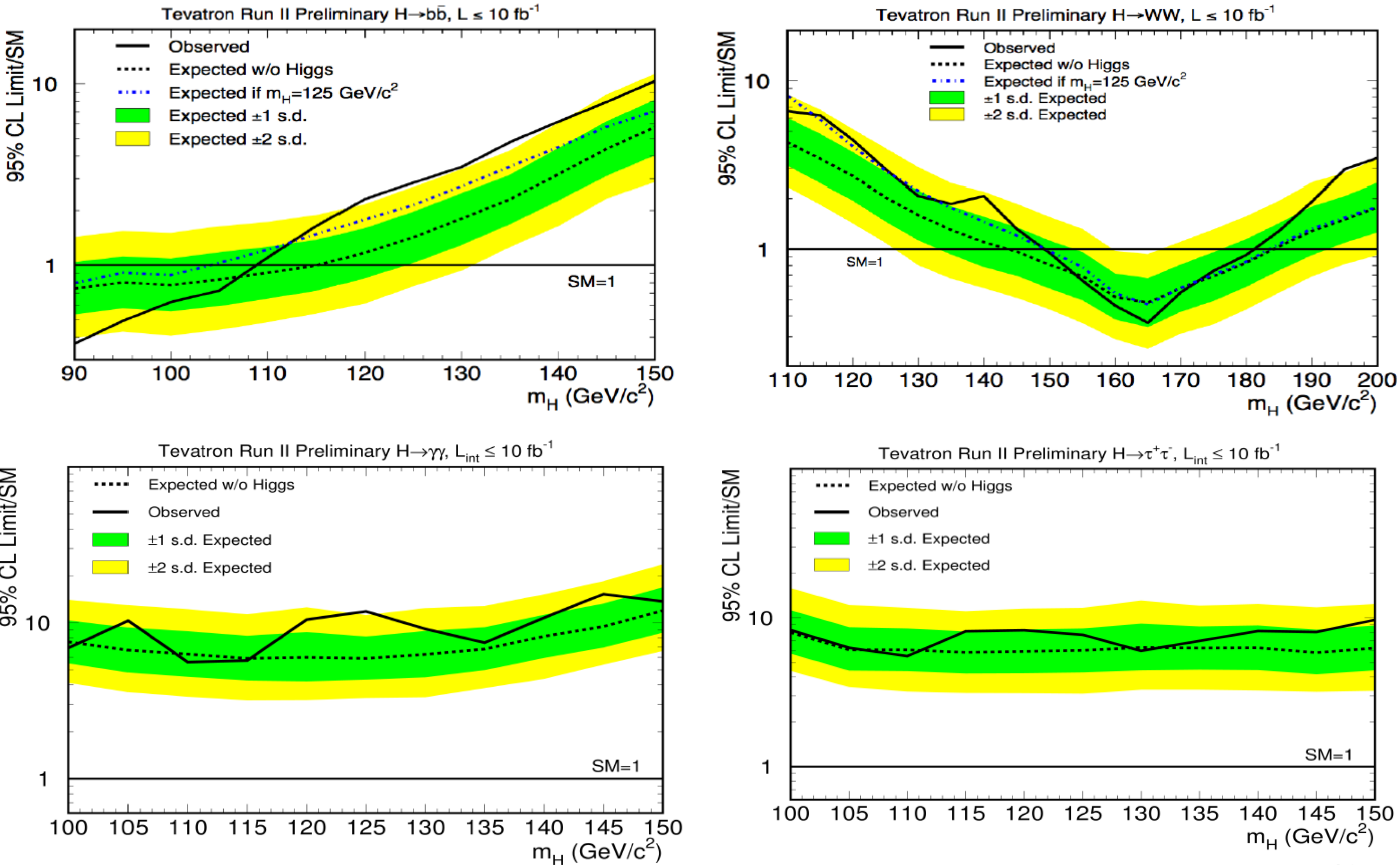


Summary

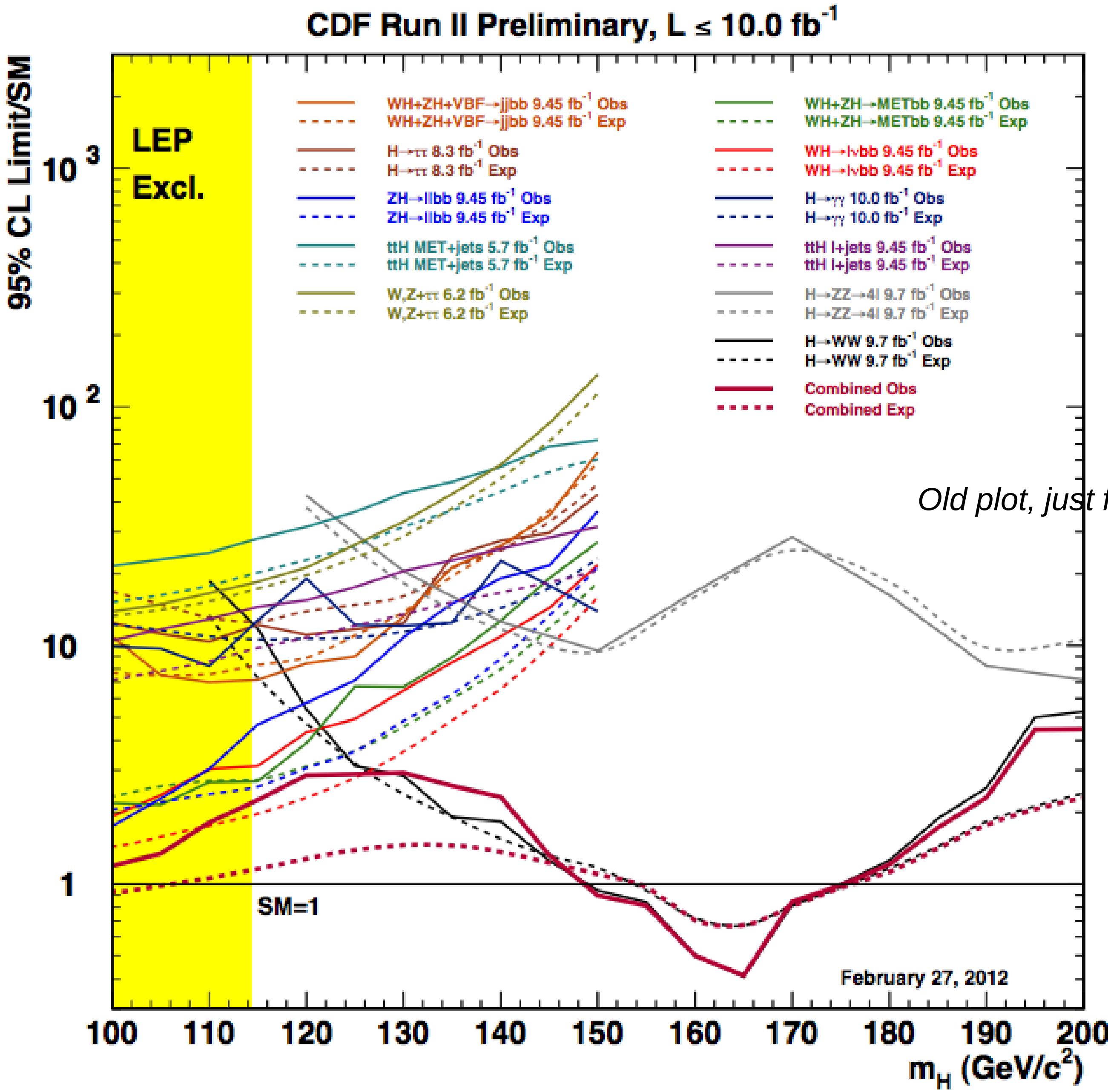
- Extensive search for Higgs boson with full Tevatron dataset.
  - Analyses evolved through Run II to state of art.
  - Excluded: $90<m_H<109$, $149<m_H<182$ GeV/c^2 (95% C.L.)
- Observed a broad excess in $115<m_H<140$ GeV/c^2.
  - Higgs Mass consistent with LHC.
  - 3.0 standard deviations at $m_H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

Backup

Tevatron Combination by Channel

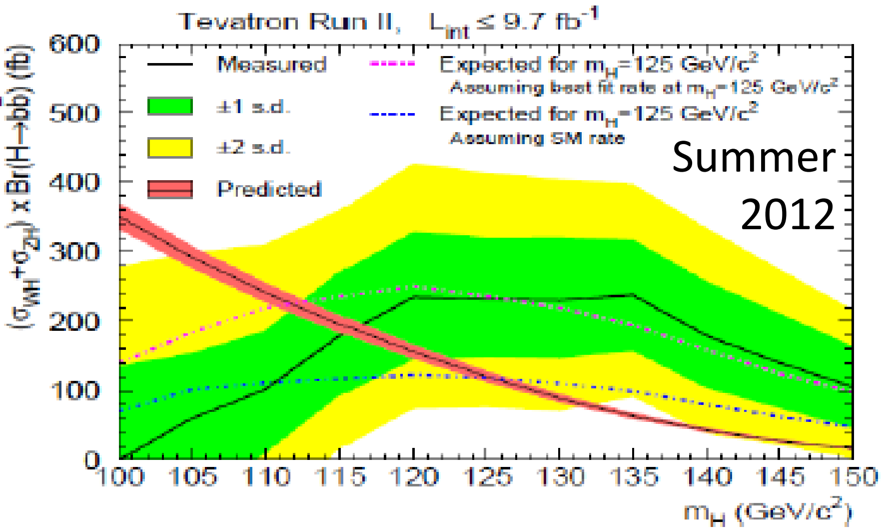


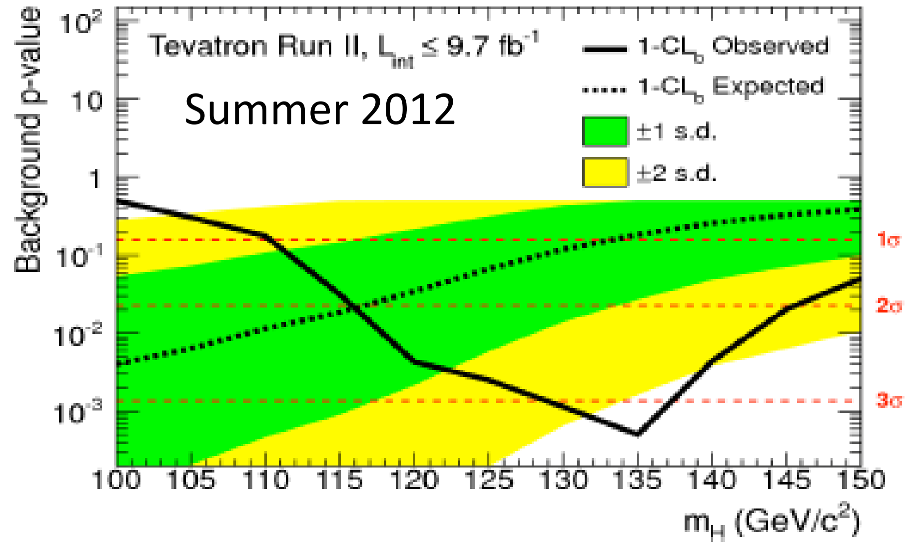
Sensitivity of Individual Channel



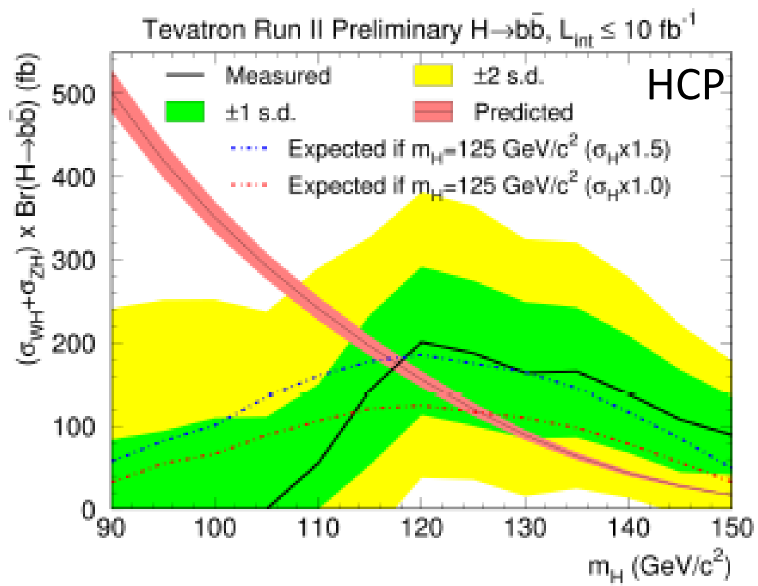
Old plot, just for illustration purposes

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

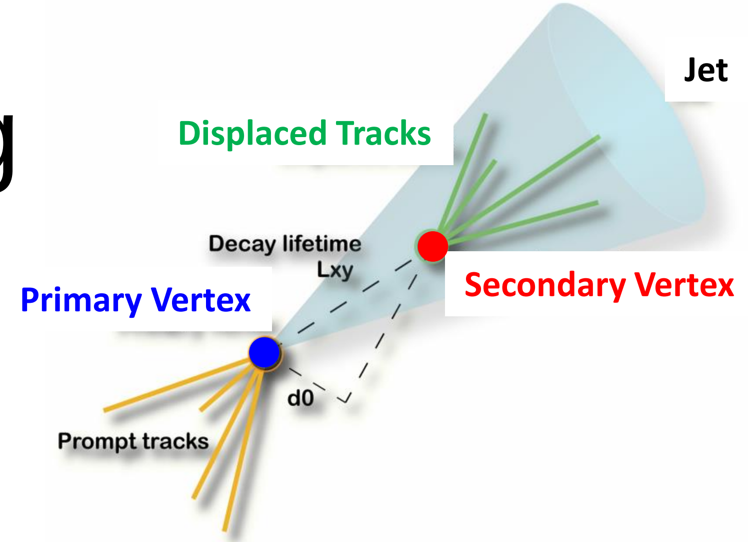




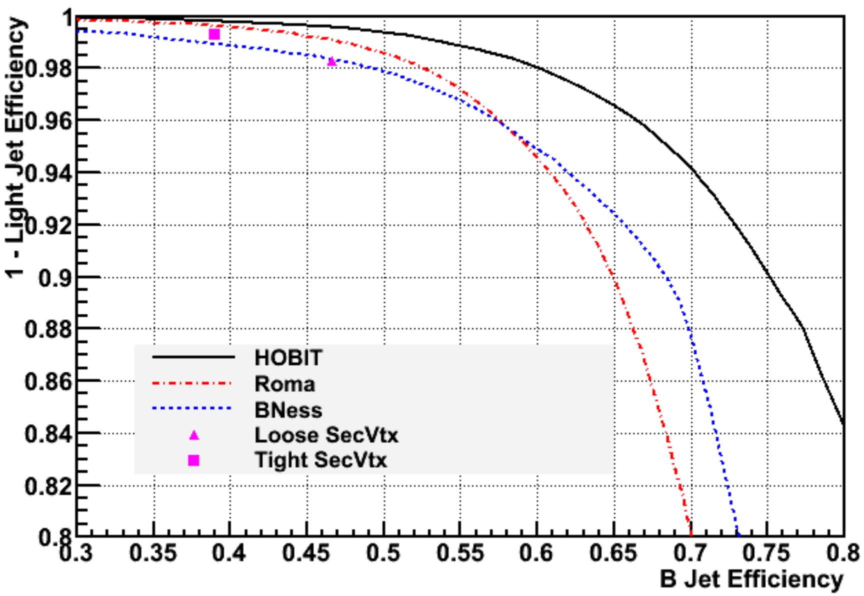
- Last Summer:
  - σ_{VH}=0.23+-0.09pb (SM:0.12+-0.01pb)@125
  - Local max p-value=3.3σ @135GeV(global p-value=3.1σ) and p-value=2.8σ @125 GeV
- HCP:
  - σ_{VH}=0.19+-0.09 pb, consistent with the summer results.
  - We find no significant issues with the previous metbb analysis and stay firmly behind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

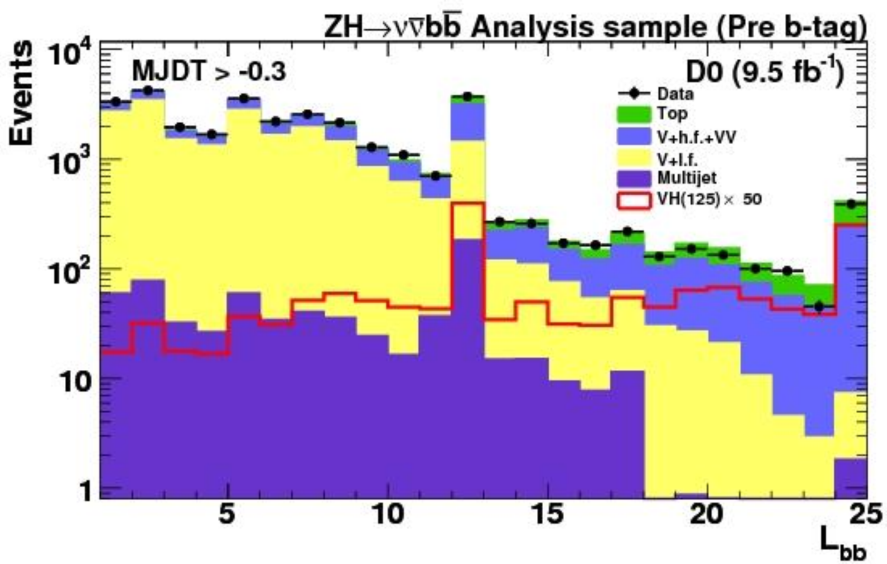


Improved *b*-tagging



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



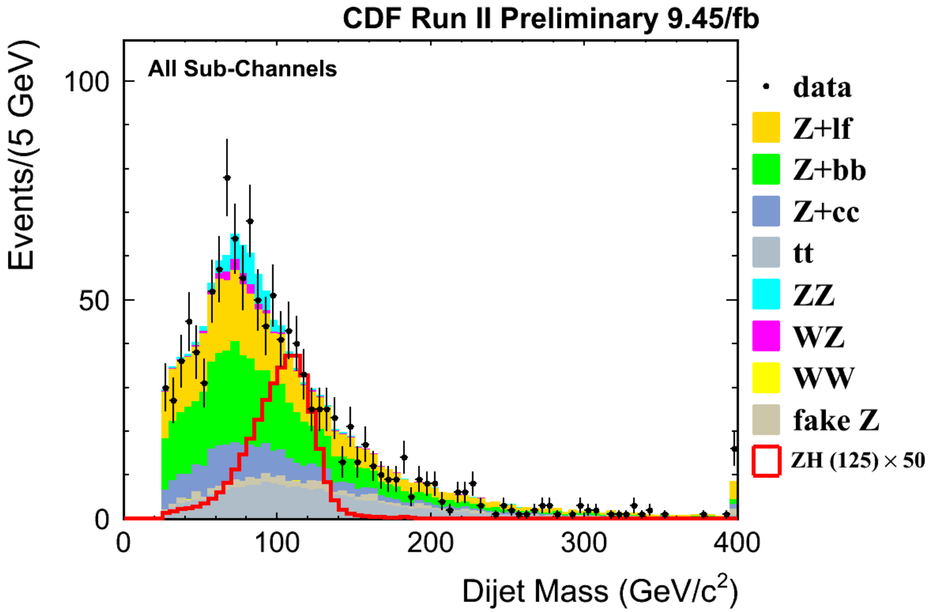


Light Flavor Eff.	HOBIT Eff.	SecVtx Eff. (old tagger)
0.89%	42%	39%
8.9%	70%	47%

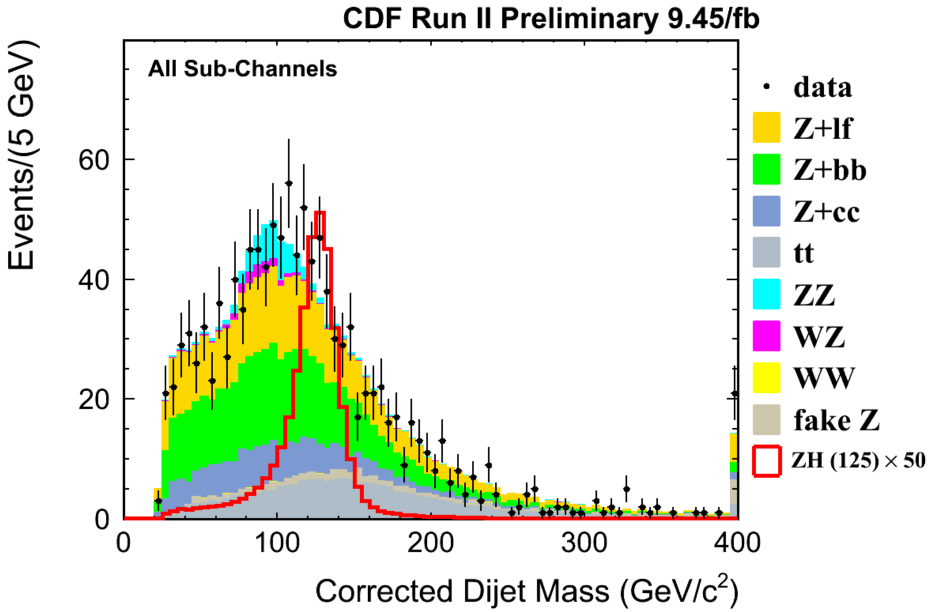
Light Flavor Eff.	Lb Eff.
0.5%	50%
4.5%	70%

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

Before NN Correction:



After NN Correction:



Resolution on $m_H \sim 11\%$

Systematics (CDF *llbb* channel)

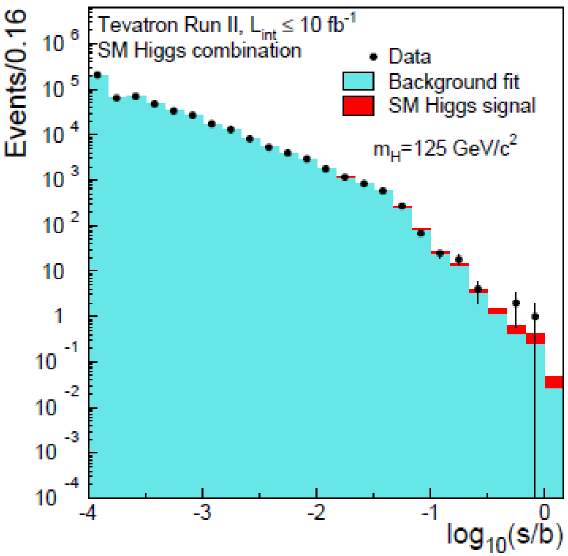
Source	%
Luminosity	6
Trigger efficiency	1-5
Lepton energy scale	1.5
ISR/FSR	1-15
B-tag efficiency	5-20
Jet energy scale	5-15
Signal xsec/br	5
Bkgd. Normalization	6-40

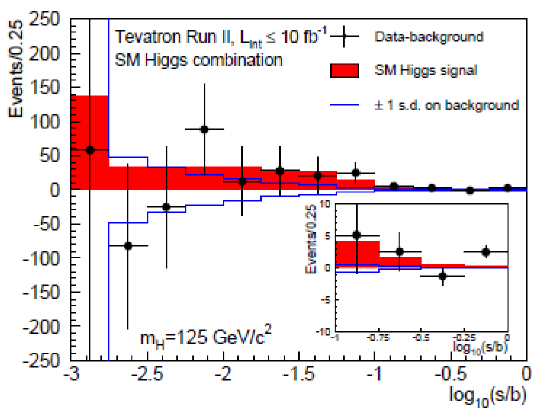
Bkgd. Process	%
Mis-ID Z	50
$Z + b\bar{b}/c\bar{c}$	40
$t\bar{t}$	10
Diboson	6

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

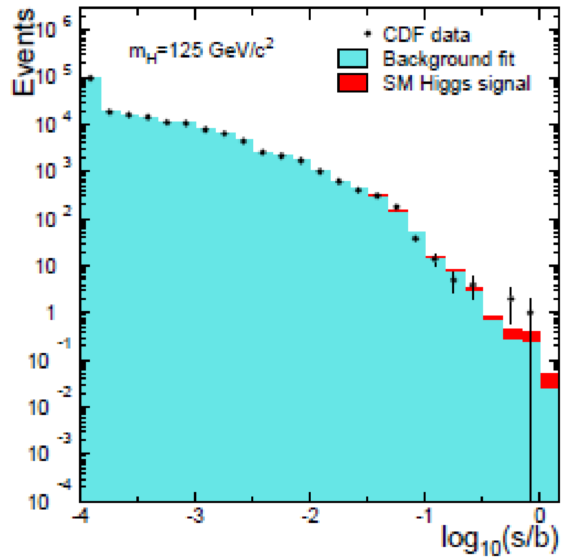
2013 Collected Event Distribution

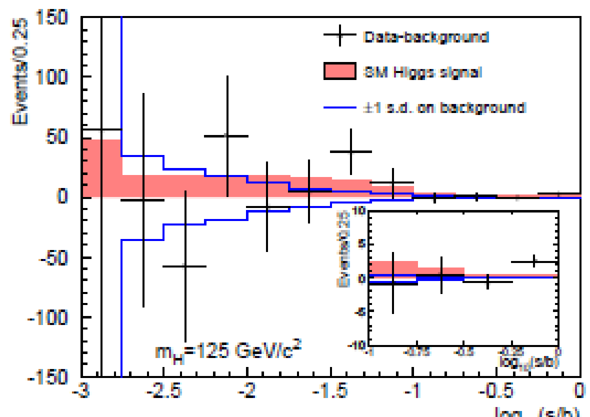
Tevatron



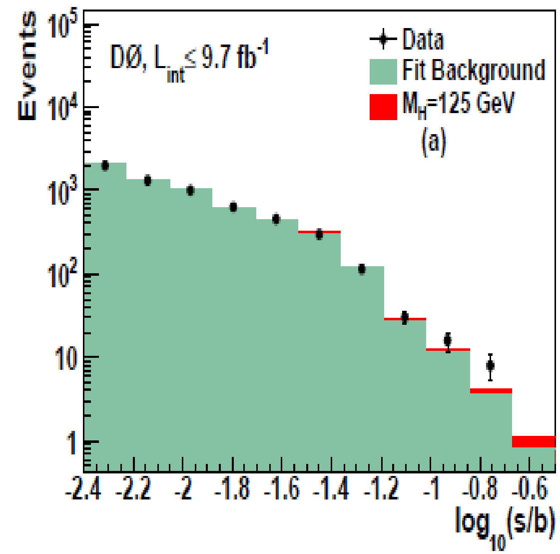


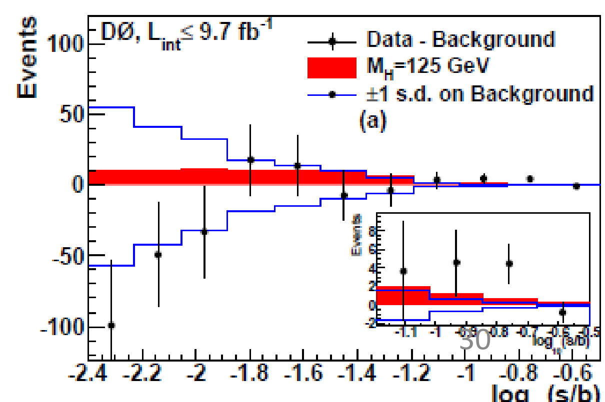
CDF



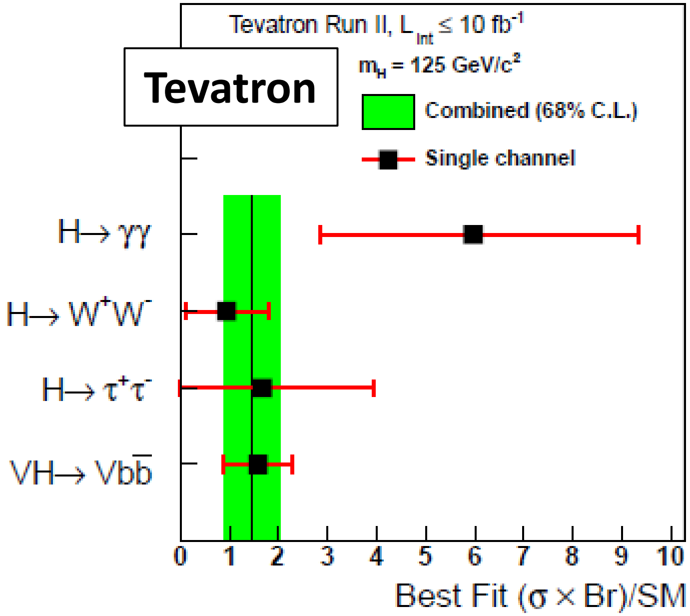


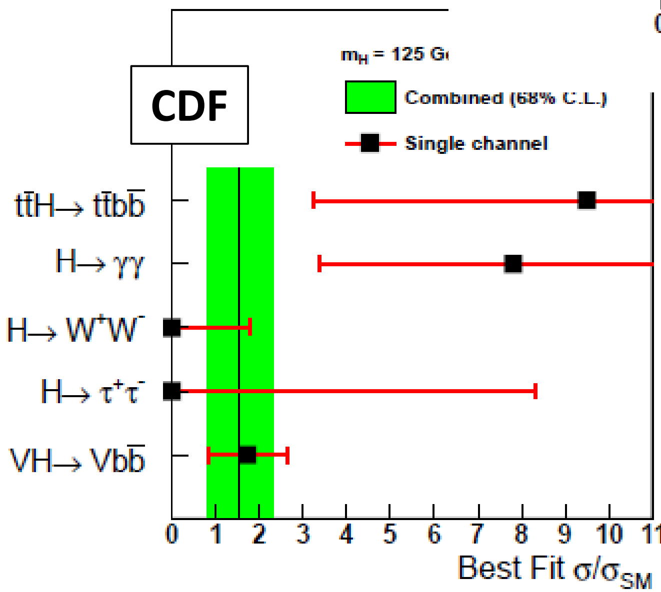
D0

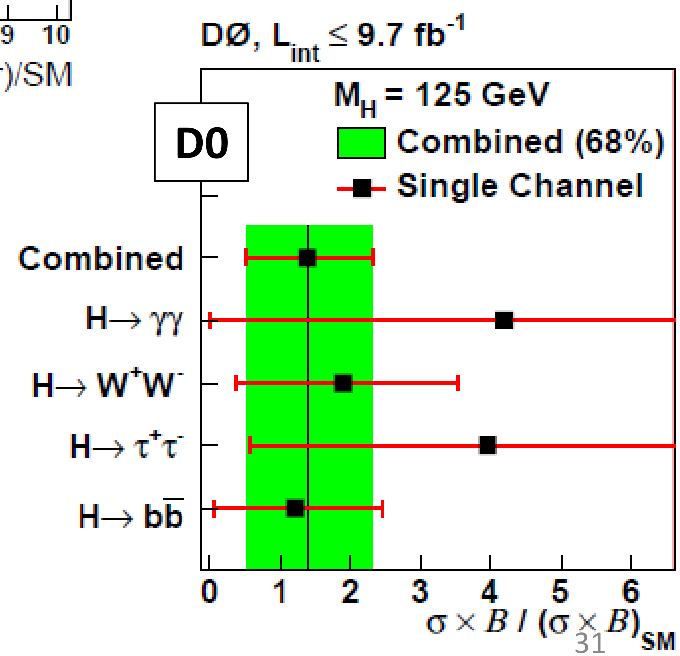




2013 Best Fit $\sigma_H \cdot Br/SM$

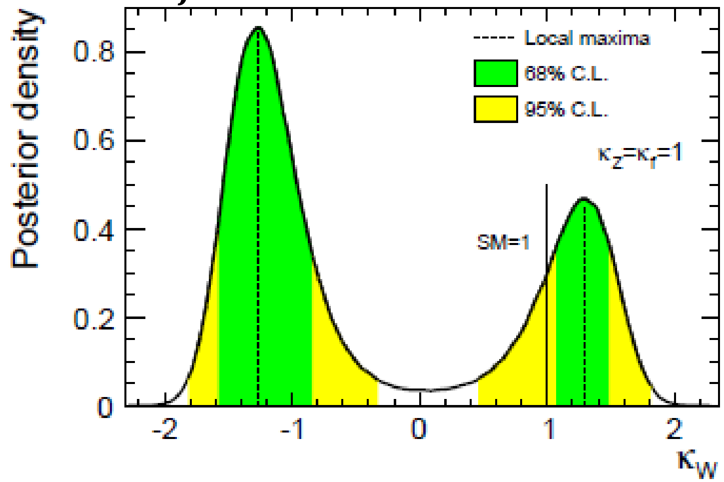




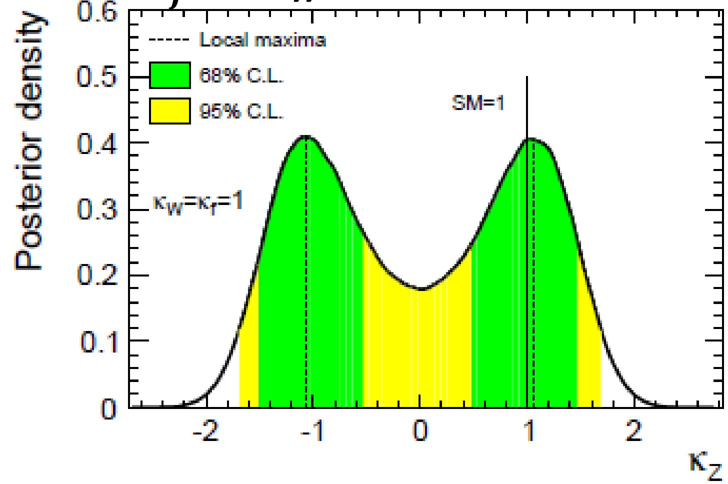


HWW, HZZ and *Hff* Couplings

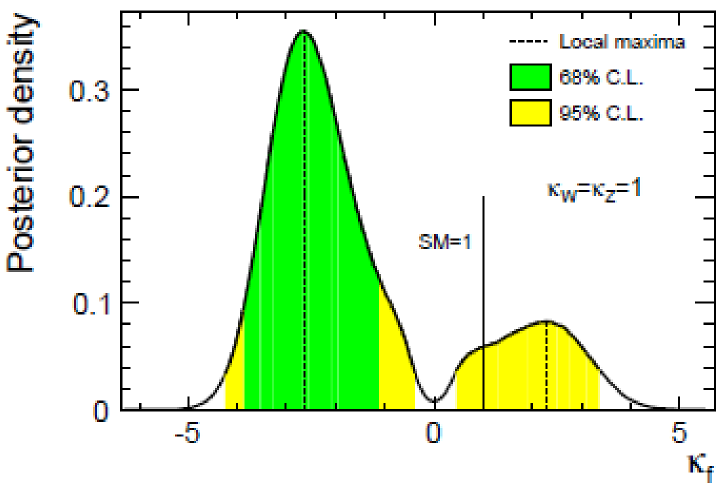
$K_f = K_Z = 1$



$K_f = K_W = 1$



$K_W = K_Z = 1$



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

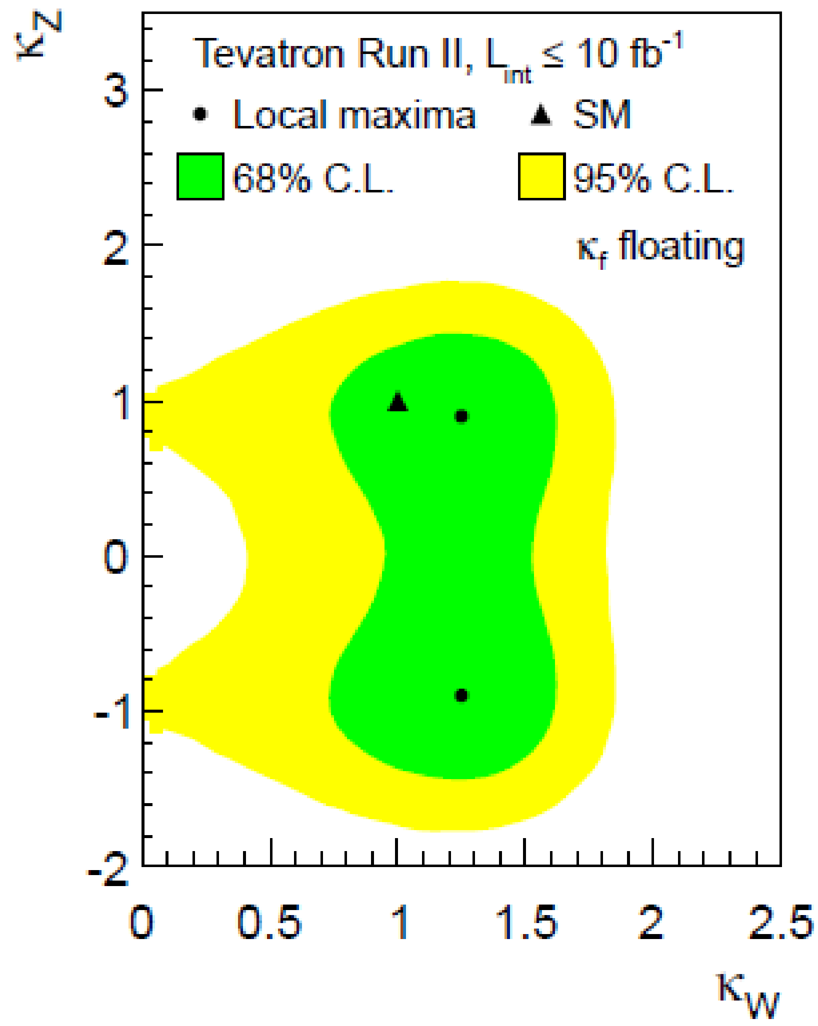
Negative values preferred for K_W and K_f due to $H \to \gamma\gamma$ excess.

HWW and *HZZ* Couplings

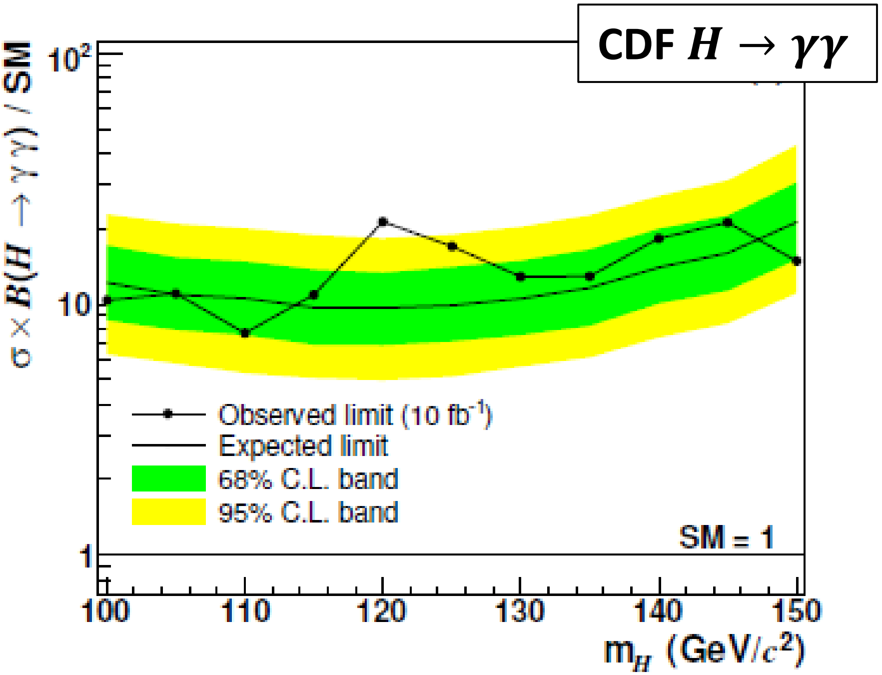
- K_f floating.

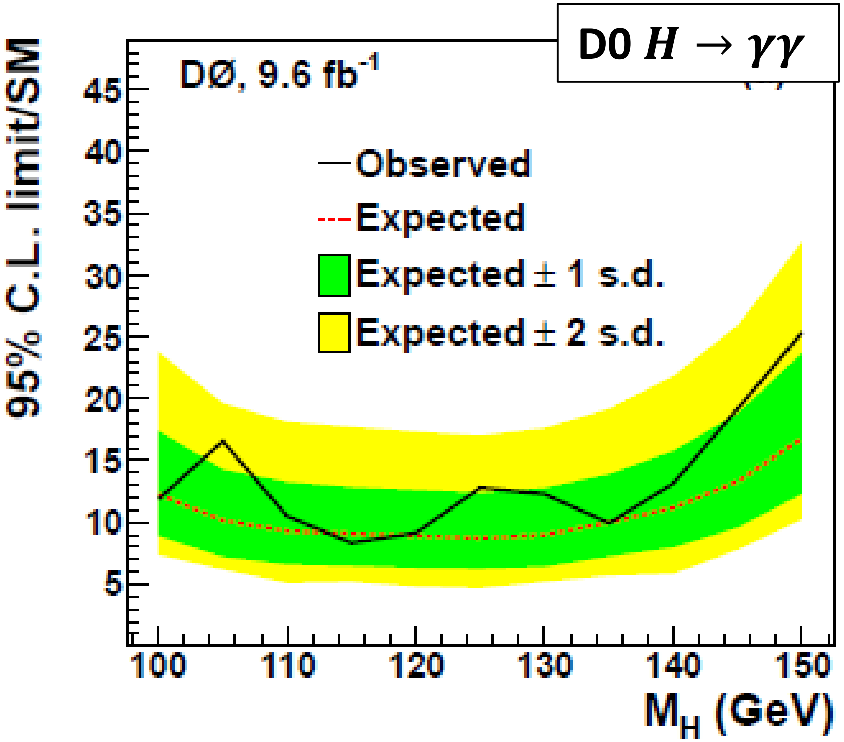
- Result is consistent with SM.
- Preferred region around:

$$(K_W, K_Z) = (1.25, \pm 0.90)$$

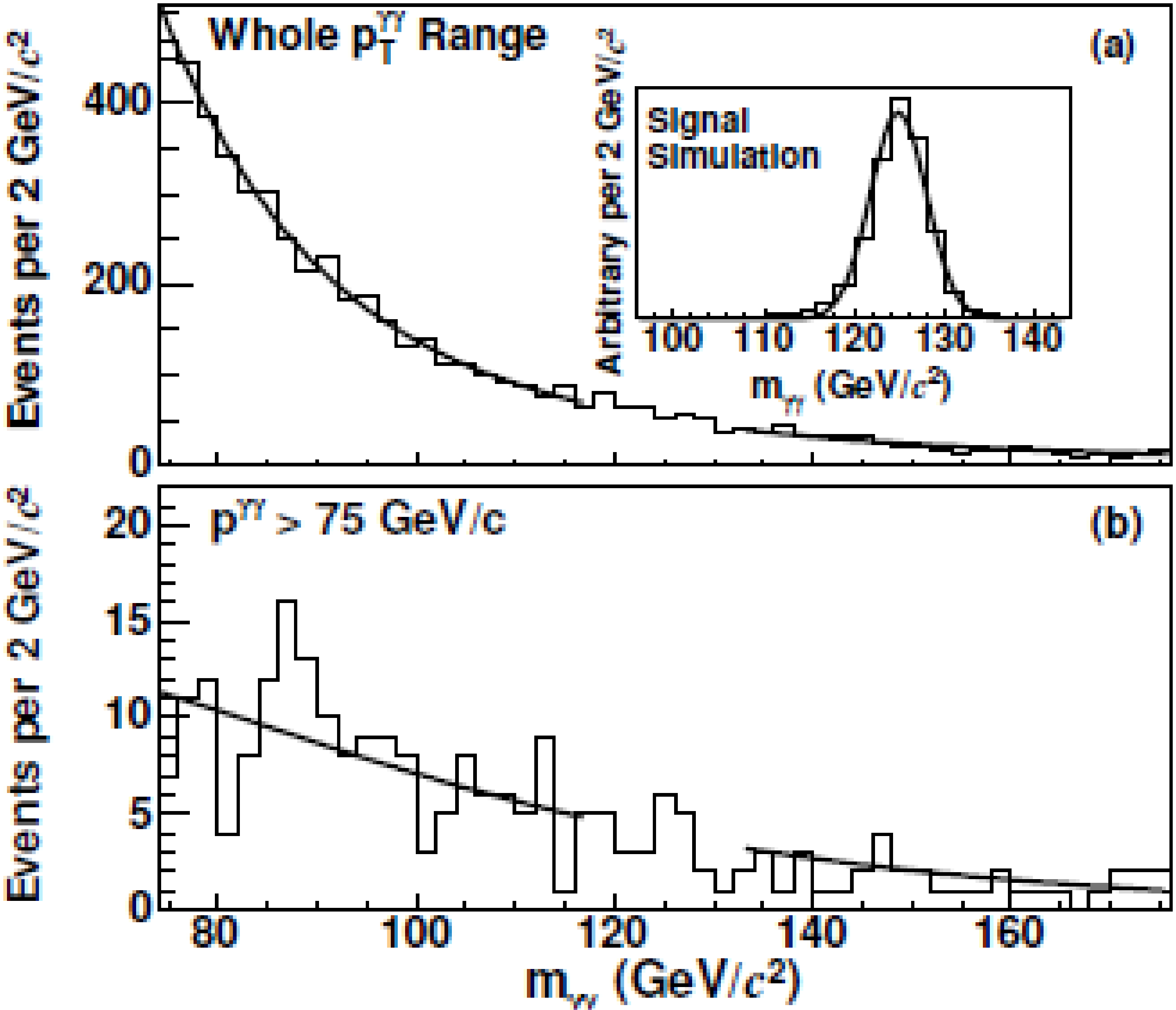


$H \to \gamma\gamma$ Limits by Experiment



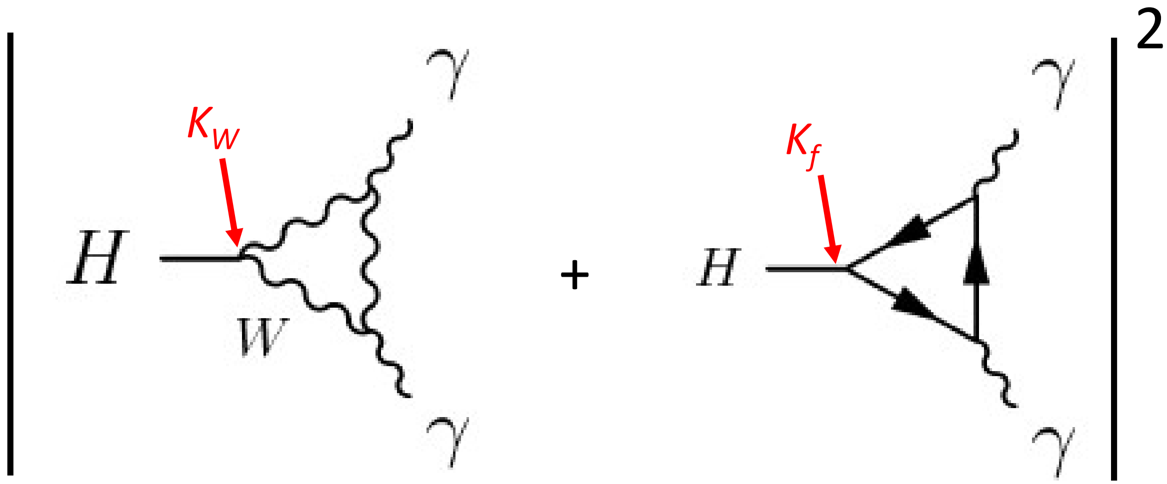


CDF H->γγ



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

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



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