# Higgs Boson Studies at the Tevatron

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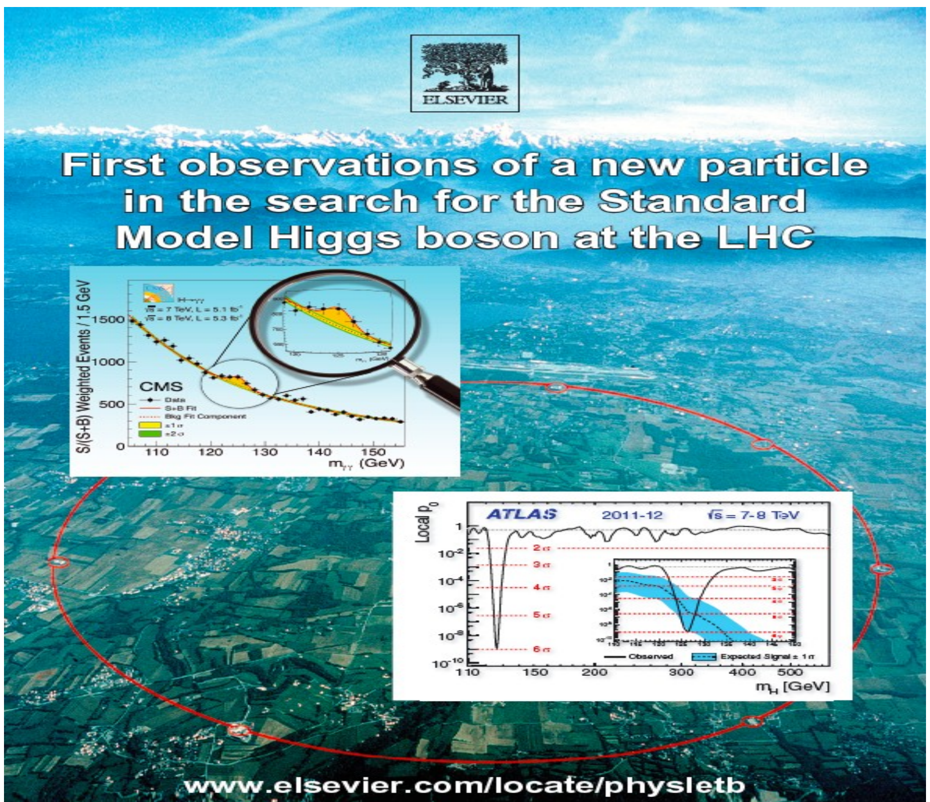
# Outline

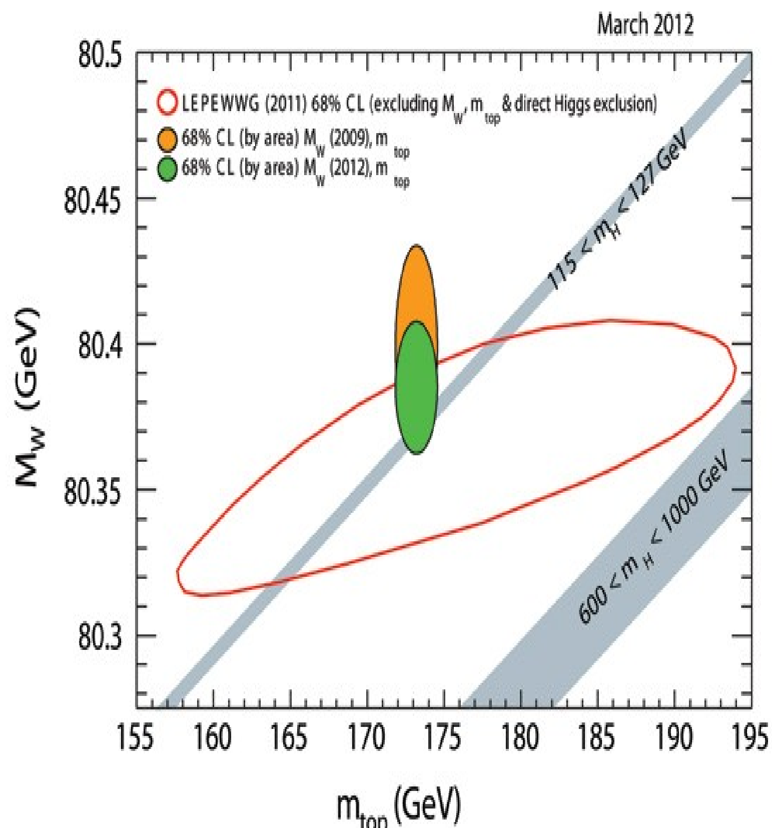
- Introduction
- Overview the Higgs search strategies at the Tevatron
- Tevatron final results  with full dataset
- Studies of the Higgs coupling and spin measurements
- Tevatron non-SM Higgs Searches
- Conclusion

- More Details:
- Tevatron Combination accepted  by PRD arXiv:1303.6346
- CDF combination accepted by  PRD arXiv:1301.6668
- D0 combination accepted by PRD arXiv: 1303.0823

# Introduction

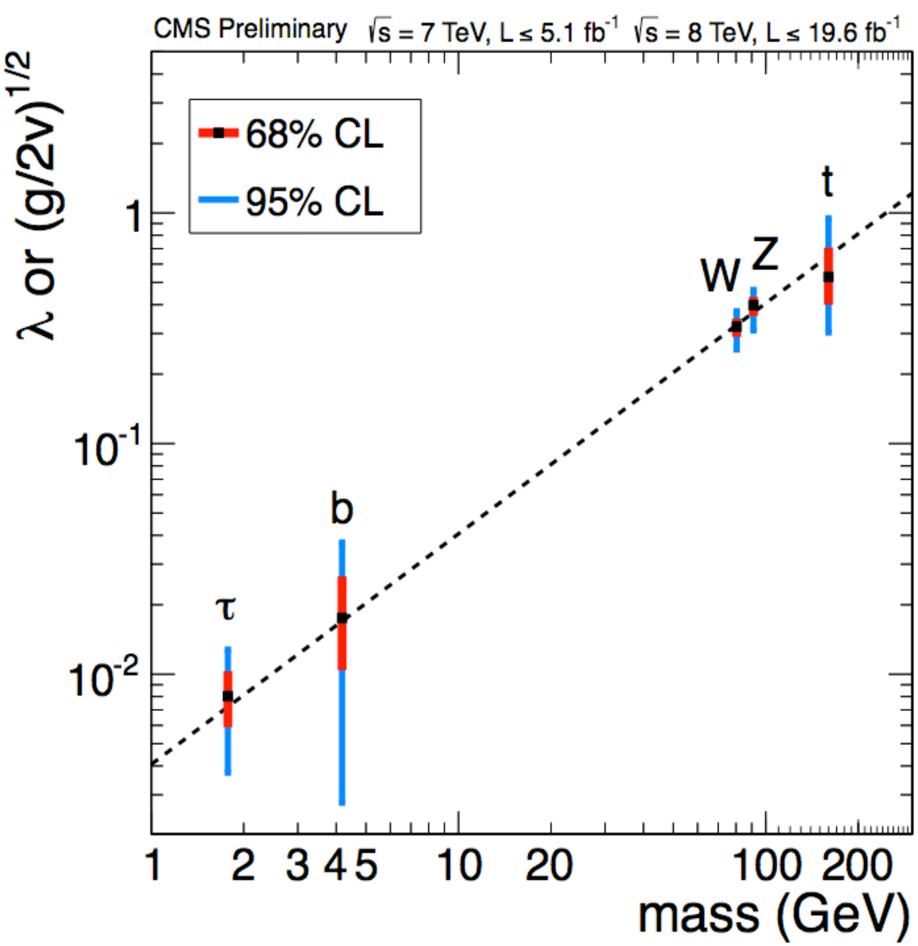
- ATLAS & CMS discovered a new boson at 125 GeV/c2 last July
- The results consistent with the expectation of a Higgs boson.
  - Most sensitivity channels at LHC are H→ZZ, γγ, WW.
  - Evidence of H→bb from Tevatron

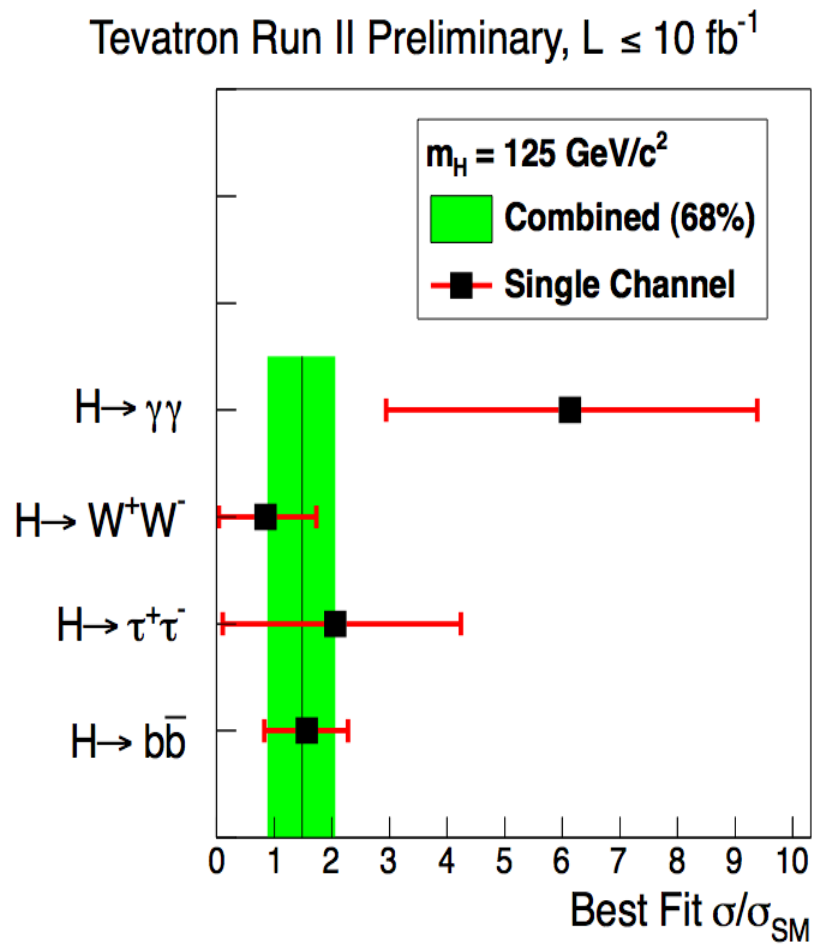


# Since the discovery

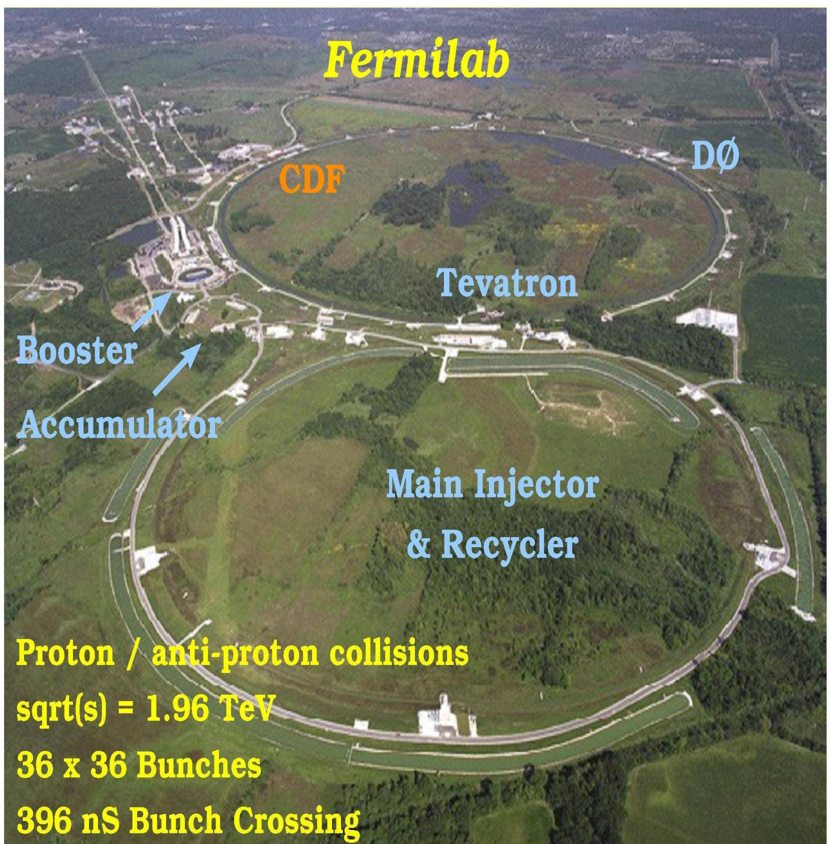
- LHC focus on studying new boson coupling and spin properties.
- Tevatron complementary as exploiting primary on H→bb decay.

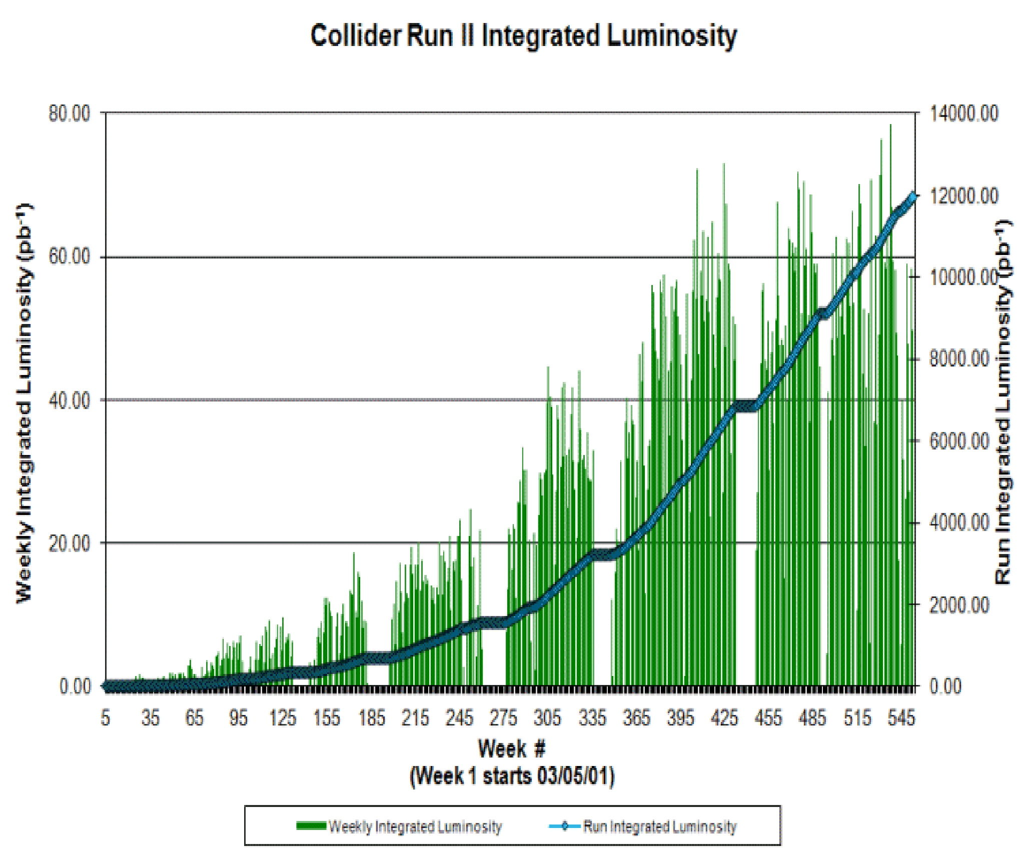


# The Tevatron

- Tevatron: p-pbar collision@1.96TeV, $L_{peak}=4.3\times10^{32}\ cm^{-2}s^{-1}$
- Delivered ~12 $fb^{-1}$ data before shutdown on 9/30/2011.
- The final results presented are based on the full dataset (~10 $fb^{-1}$)



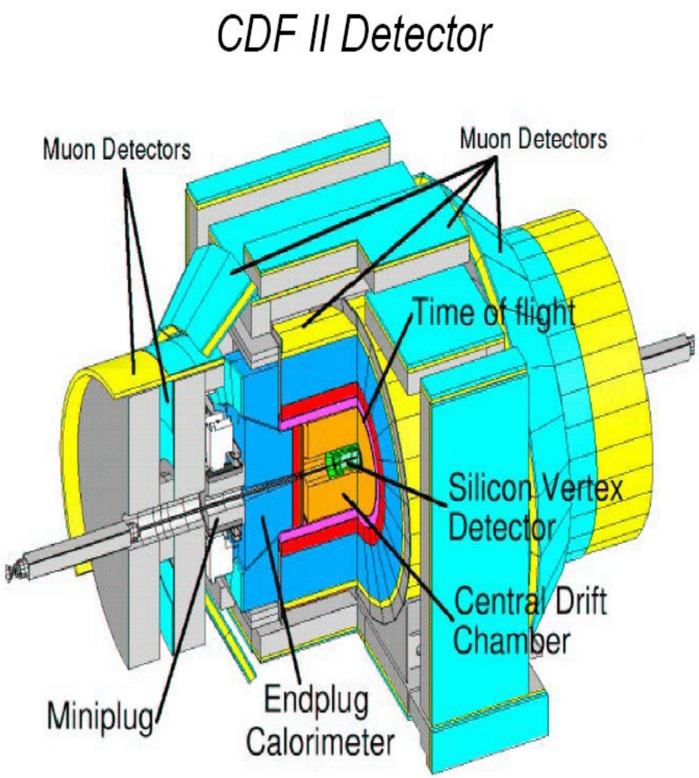



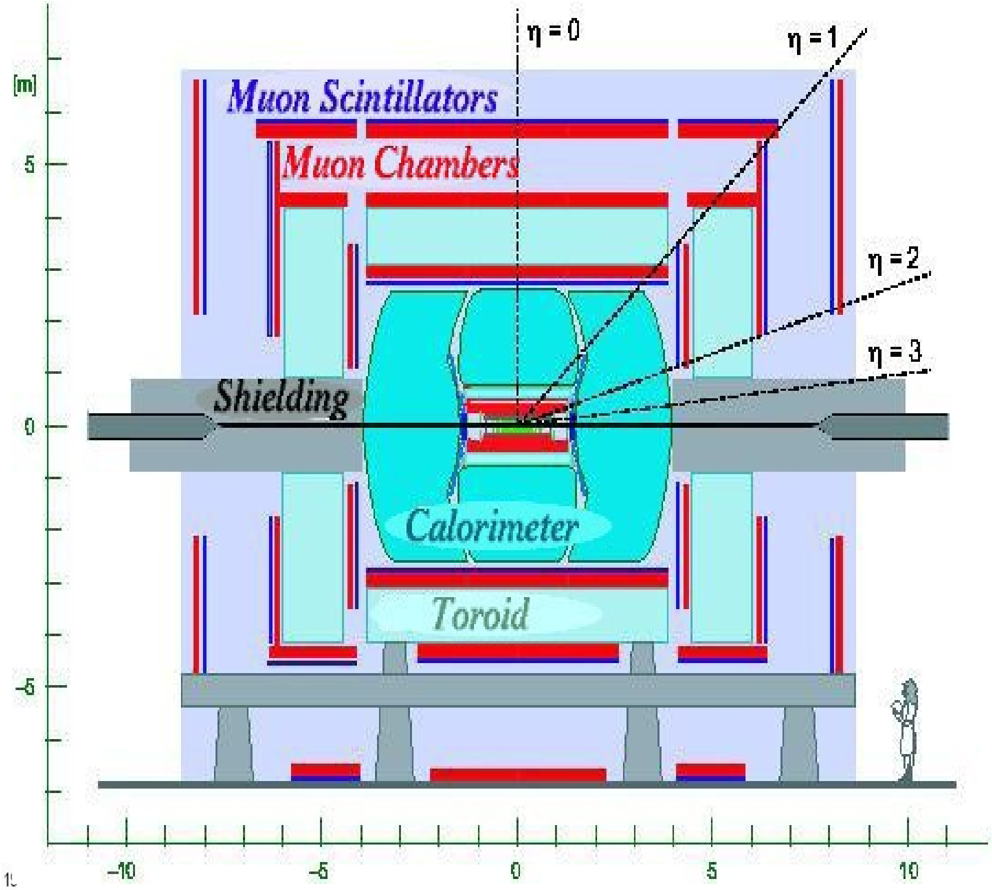
# A remarkable discovery machine

- 1995 Top quark
- 1998 Bc meson
- 2006 Bs oscillations
- 2006 Sigma-b baryon
- 2007 Cascade-b baryon
- 2008 Omega-b baryon
- 2009 Single top quark production
- 2011 Xi-b baryon
- 2012 World's best W and top mass measurements
- 2012 Evidence of the H→bb

# CDF & D0 General-purpose Detectors

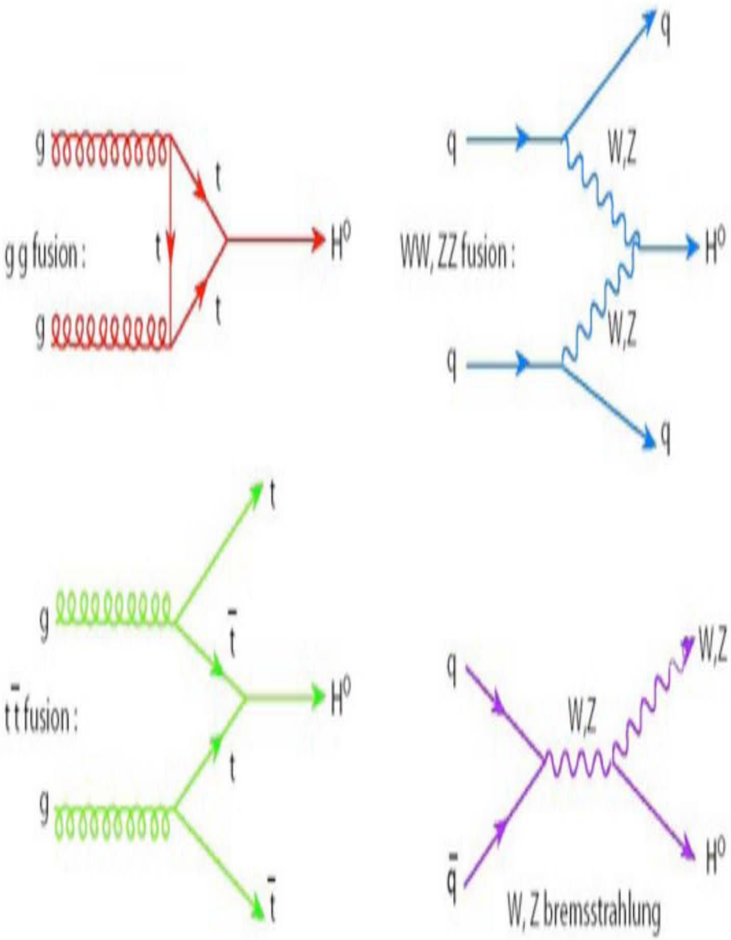
- Provides excellent lepton id, tracking, vertexing, jets, and missing Et
- Multi-level triggers to select interesting events with combination of signatures.
- Tevatron experience has been a major contributor to the sussess of LHC.

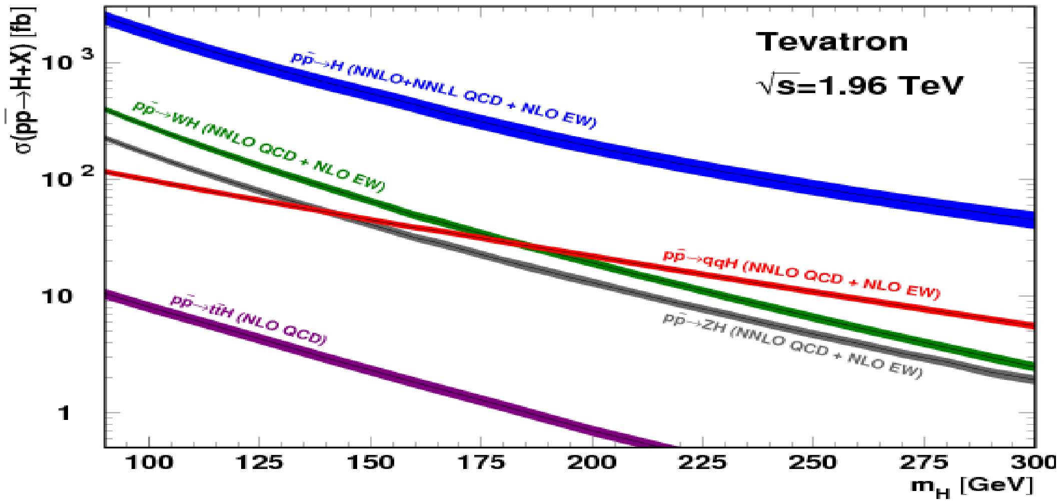


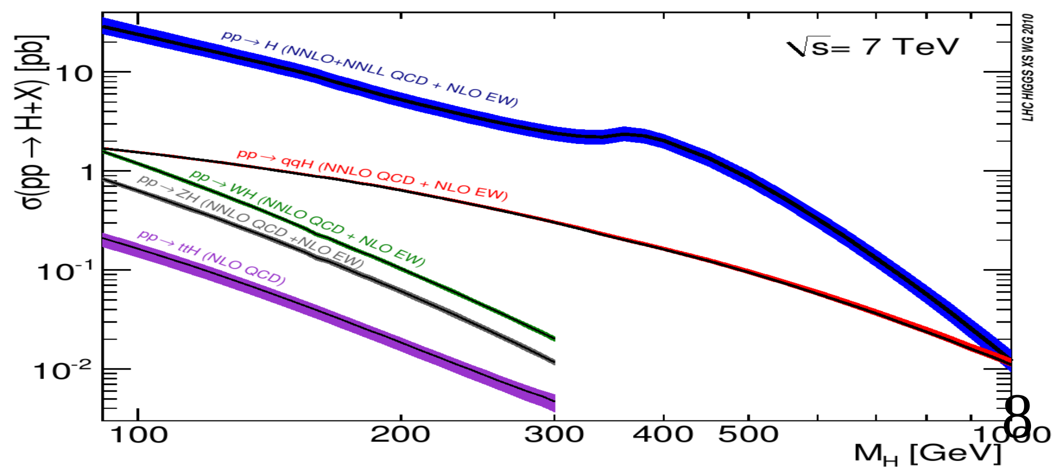



# Higgs Production

- Higgs predominately produced via ggF & VH production at Tevatron.
- Energy & initial state very different than LHC: unique for H→bb search.

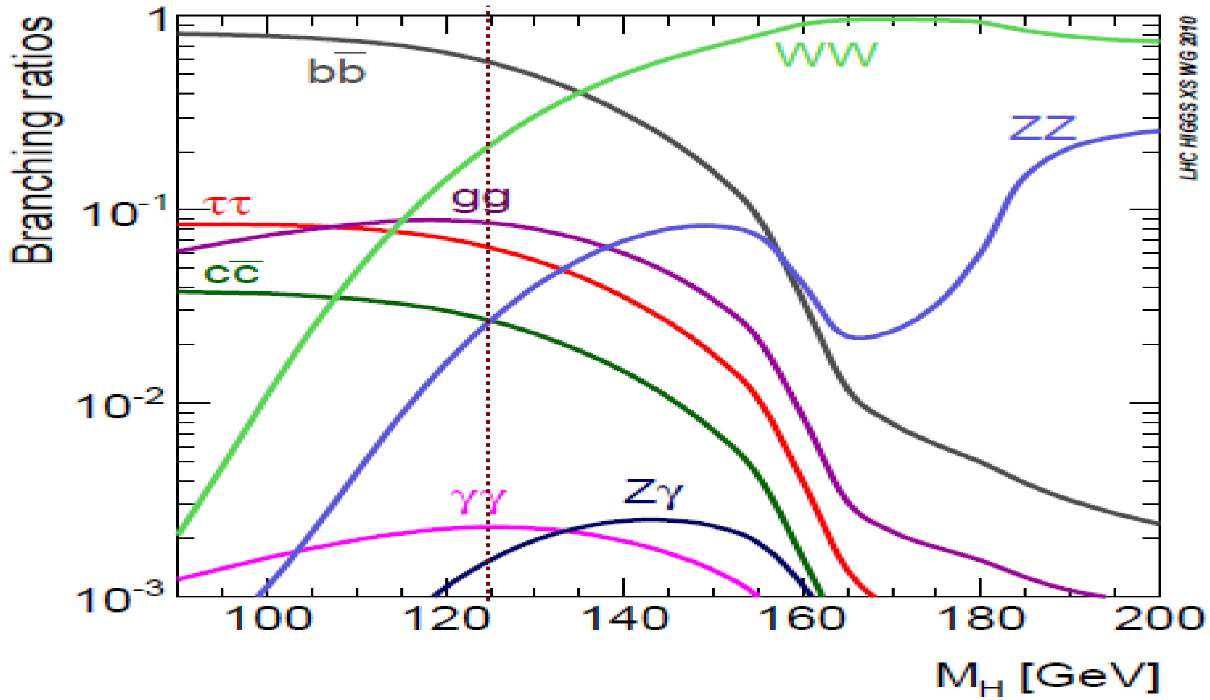


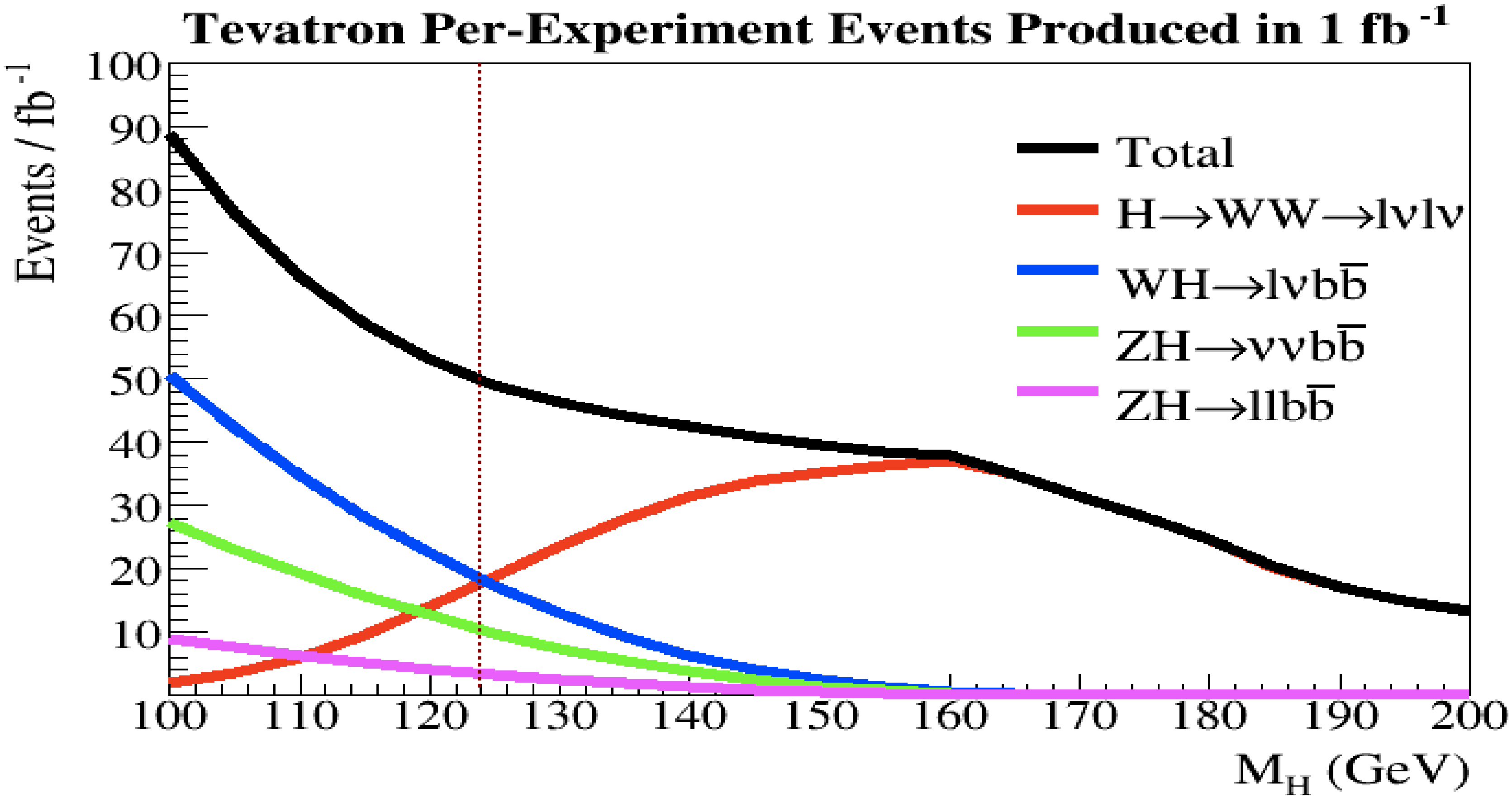
# Standard Model Higgs Decays

- Decay modes change as a function of $m_H$.
- Divide into low, intermediate, and high mass regions.
- Low mass: dominant decay (bb) is difficult due to QCD:
  - Tevatron:VH→bb, H→WW
  - LHC: H→γγ,ZZ,WW.



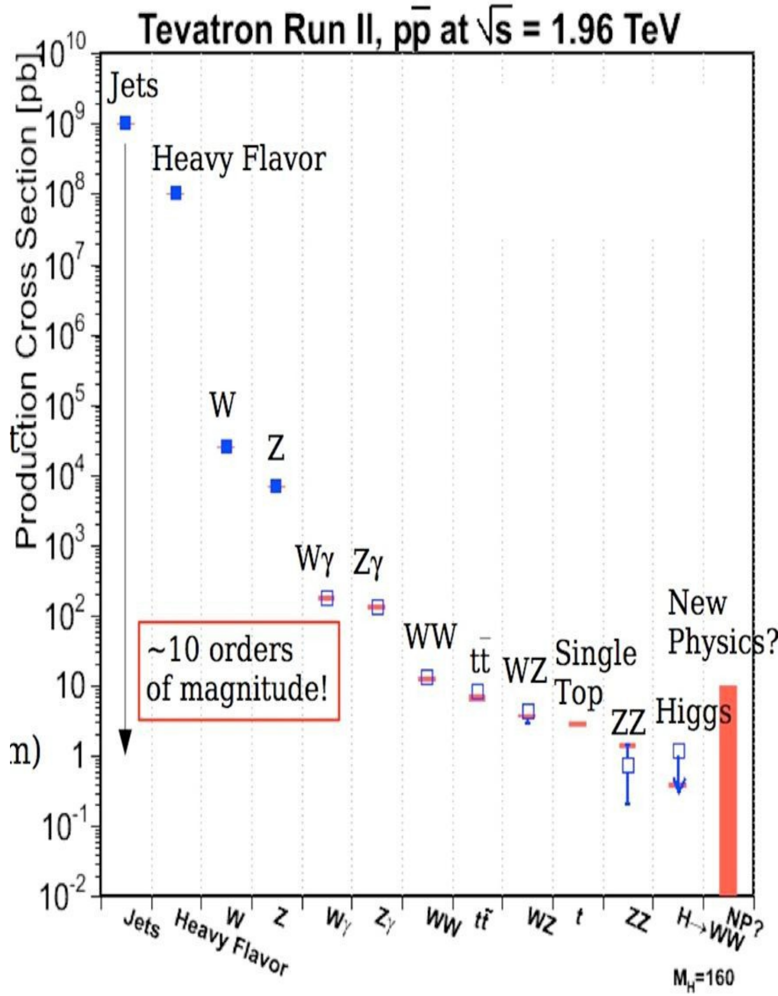
# Higgs Search Strategies

- For $m_H$=125 GeV/$c^2$, there are about 50 Higgs events produced per inverse femtobarn per experiment at the Tevatron.
- With 10/fb per experiment, over 1000 total higgs events to find.



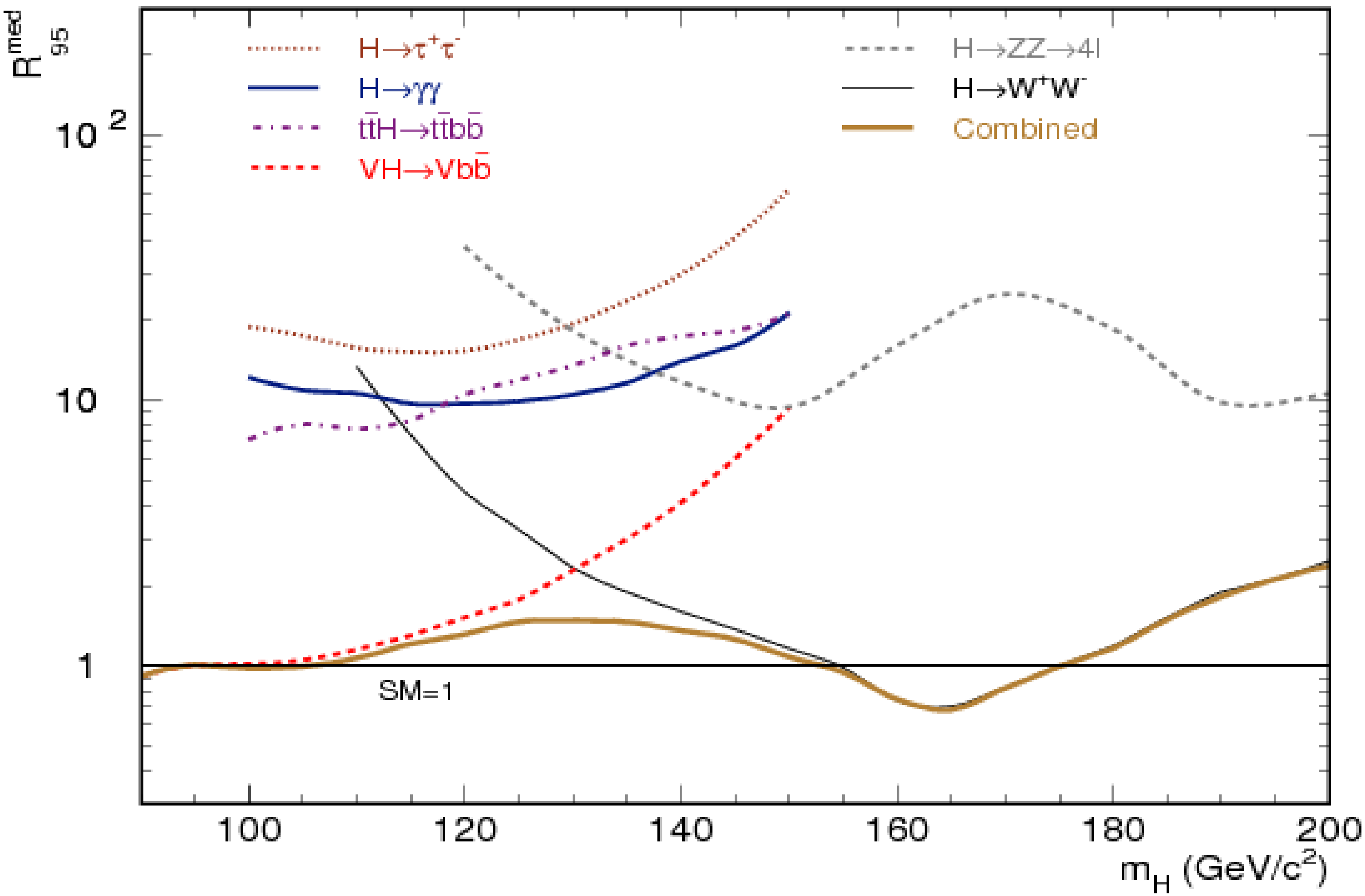
# The Challenge

- The challenge is to separate the tiny Higgs signal from the huge background of SM processes with the same final states.
- Search strategy has evolved over years:
  - –Maximizing signal acceptances using efficient triggers, lepton ID, and b-tagging that improves S/B to ~1/100.
  - –Using multivariate analysis (MVA) to exploit kinematic differences of S and B that improves S/B to ~1/10.
- The procedures are iterated until the best sensitivity is achieved.



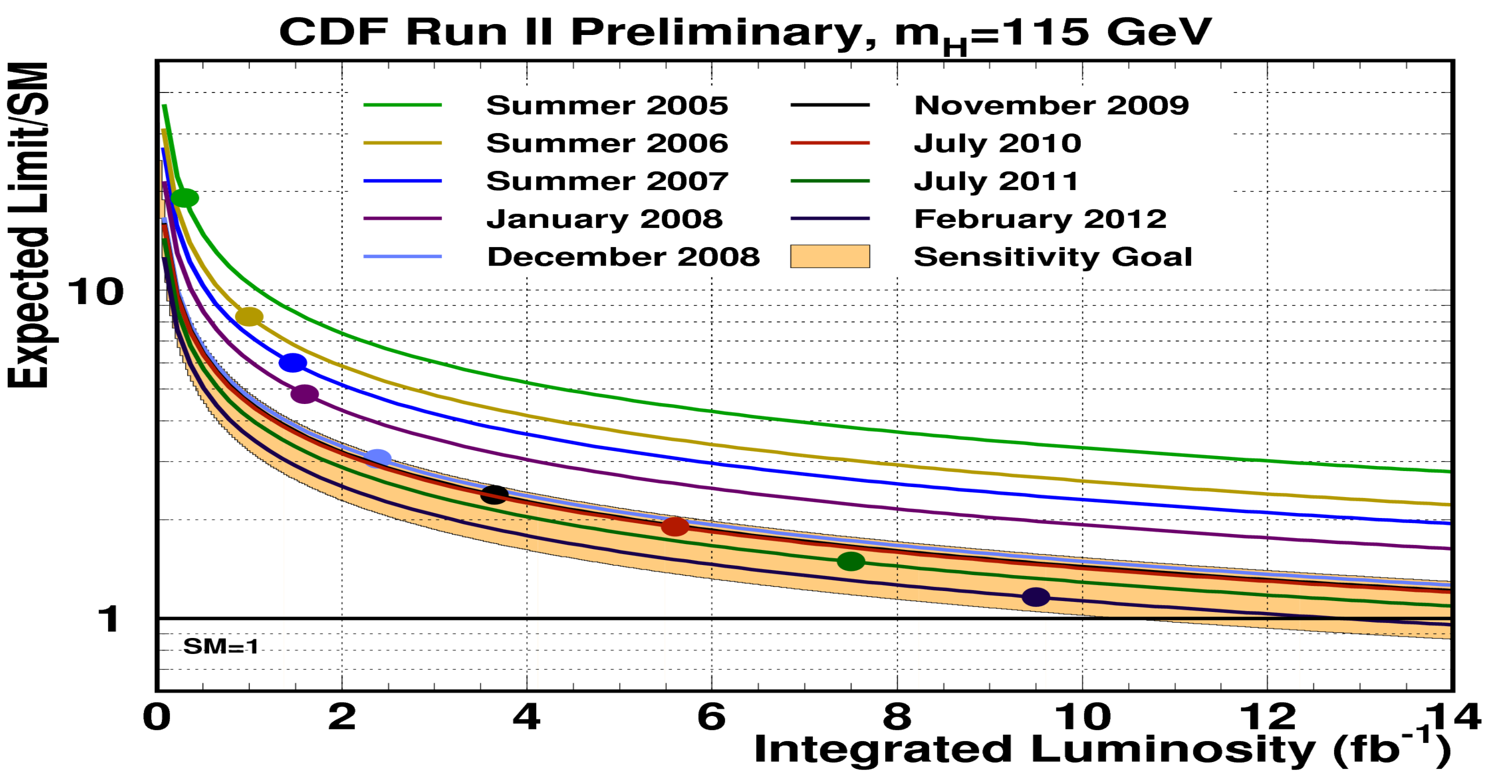
# Higgs Sensitivity at the Tevatron

- Higgs sensitivity, $R^{med}_{95} = \sigma x B/(\sigma x B)^{SM}$ at 95% CL, by channels.

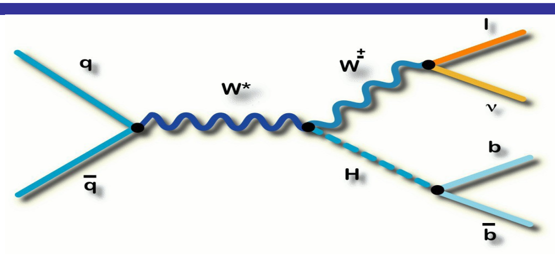


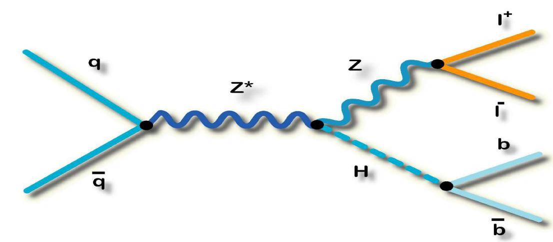
# Sensitivity Improvement

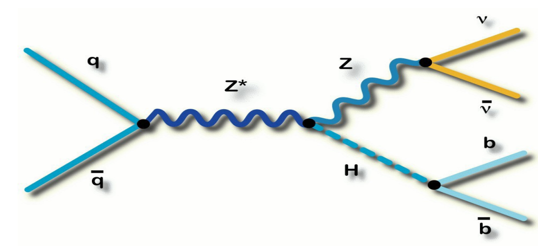
- We constantly introduced and improved analysis techniques that boost sensitivity beyond expectation from increased luminosity.
- Orange band corresponds to our conservative and aggressive sensitivity projection based on 2007 summer results.



# Search for H→bb

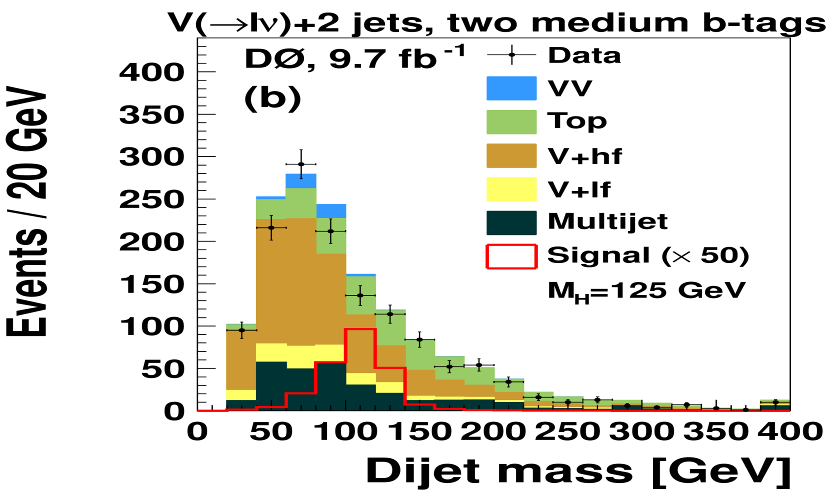


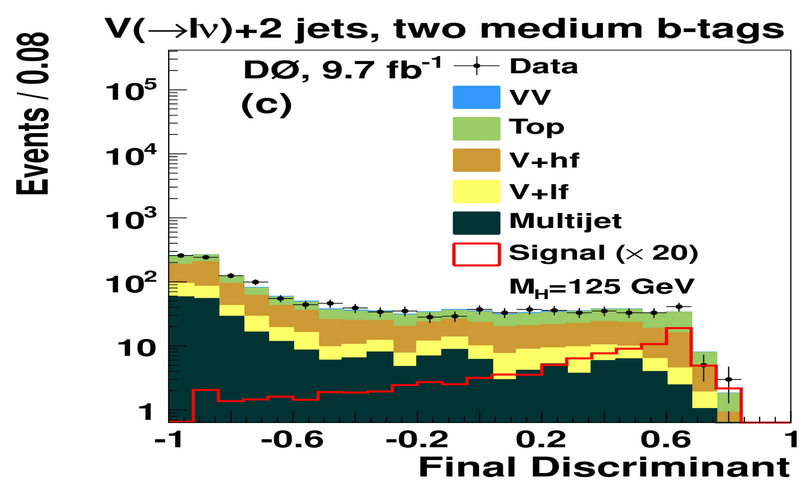




- Search for H→bb resonance in association with W or Z in three main channels.
- Most sensitivity channels is WH→lvbb: one lepton + MET+bb
- Requiring b-tagging and use advanced multivariate analysis (MVA) to further suppress the background with gain of 25% in sensitivity.

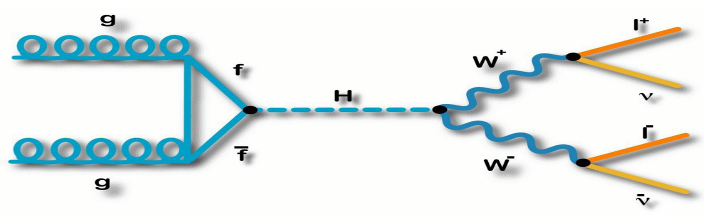
**WH→lvbb**

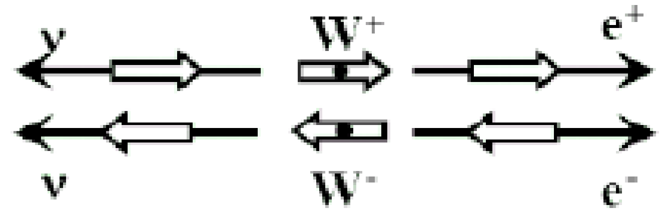



MVA



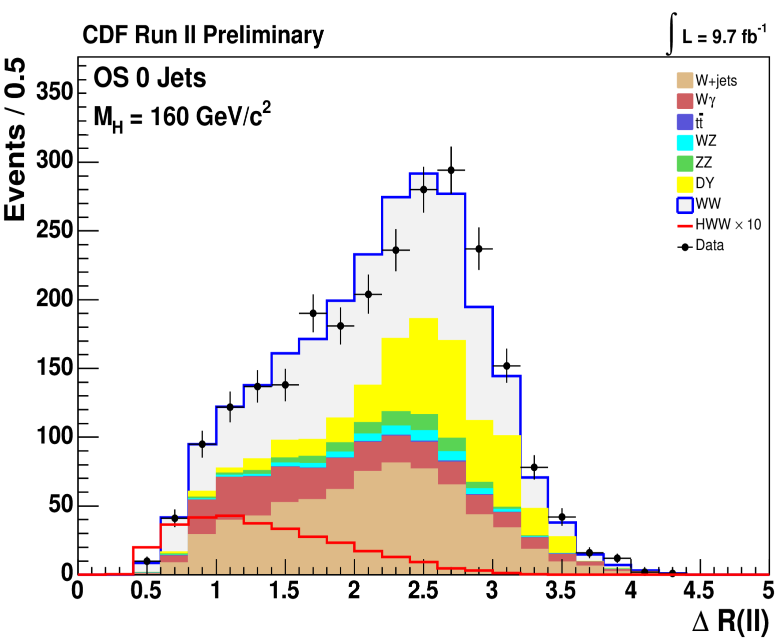
# High Mass Signatures

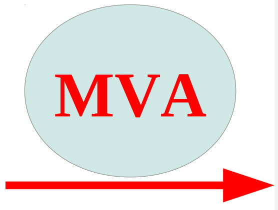


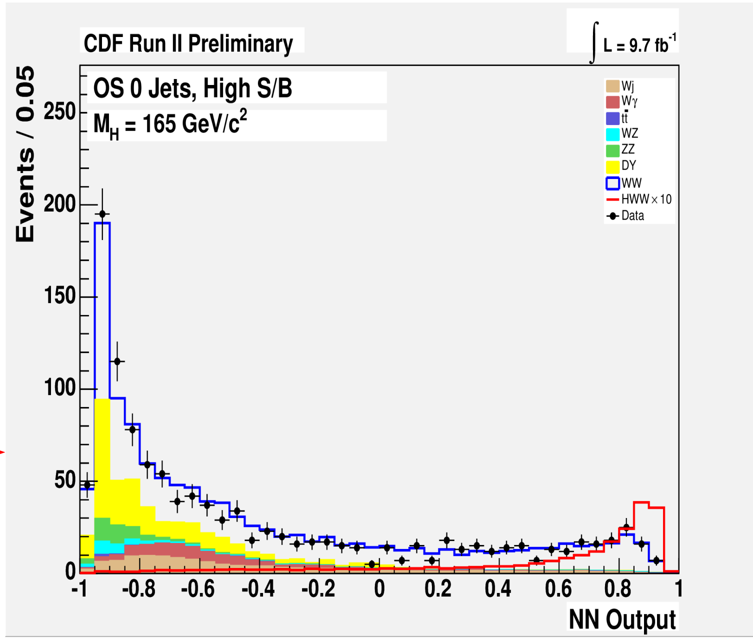




- Search for H→WW that leads to many interesting final states.
- Most sensitive channel is H→WW→lνlν: OS dilepton+met+0,1,2jets
- Requiring MVA to separate signal from main backgrounds (WW, ttbar)

**H→WW→lνlν**

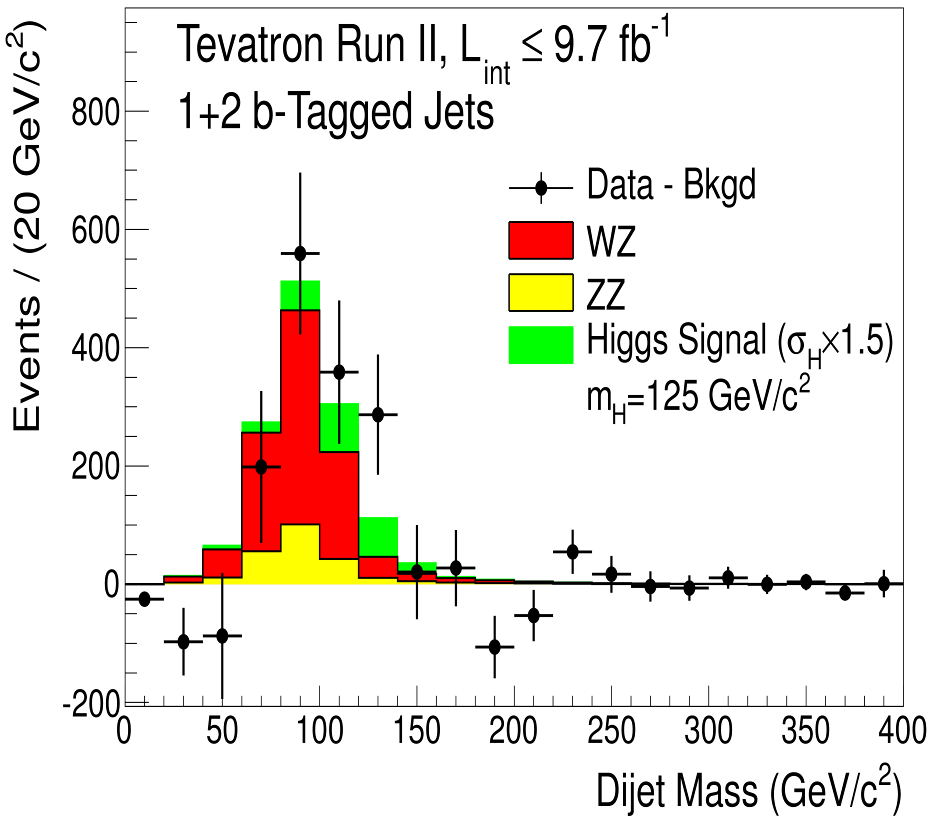


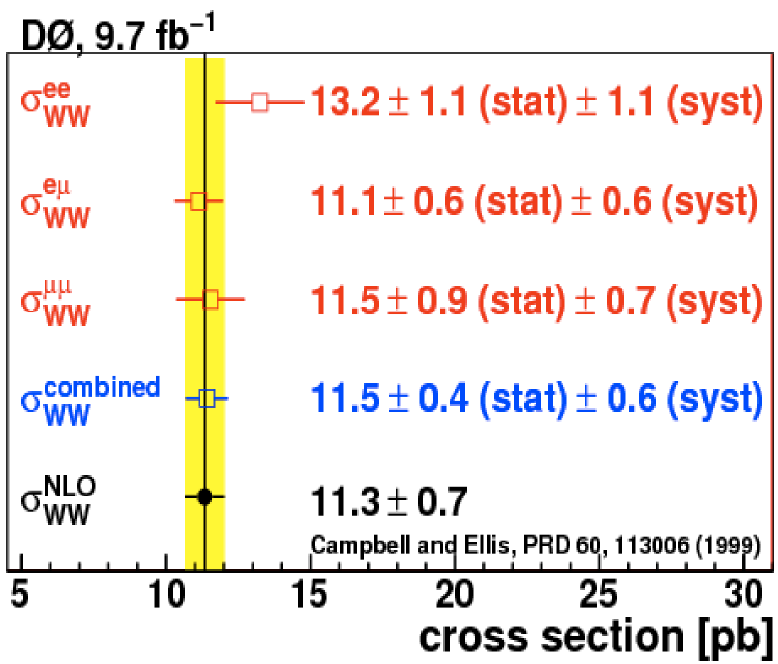



# Validation of Search Strategies

- Looking for known SM processes with same signatures and analysis tools.
  - H→bb search: look for Z→bb in WZ/ZZ→lvbb, llbb, and vvbb with measured $\sigma_{WW+WZ}$=(3.0+-0.9) pb, in good agreement with SM prediction of 4.4±0.3 pb.
  - H→W+W- search: look for SM WW production in WW→lvlv decay.



# Combined Limits on SM Higgs Boson Production

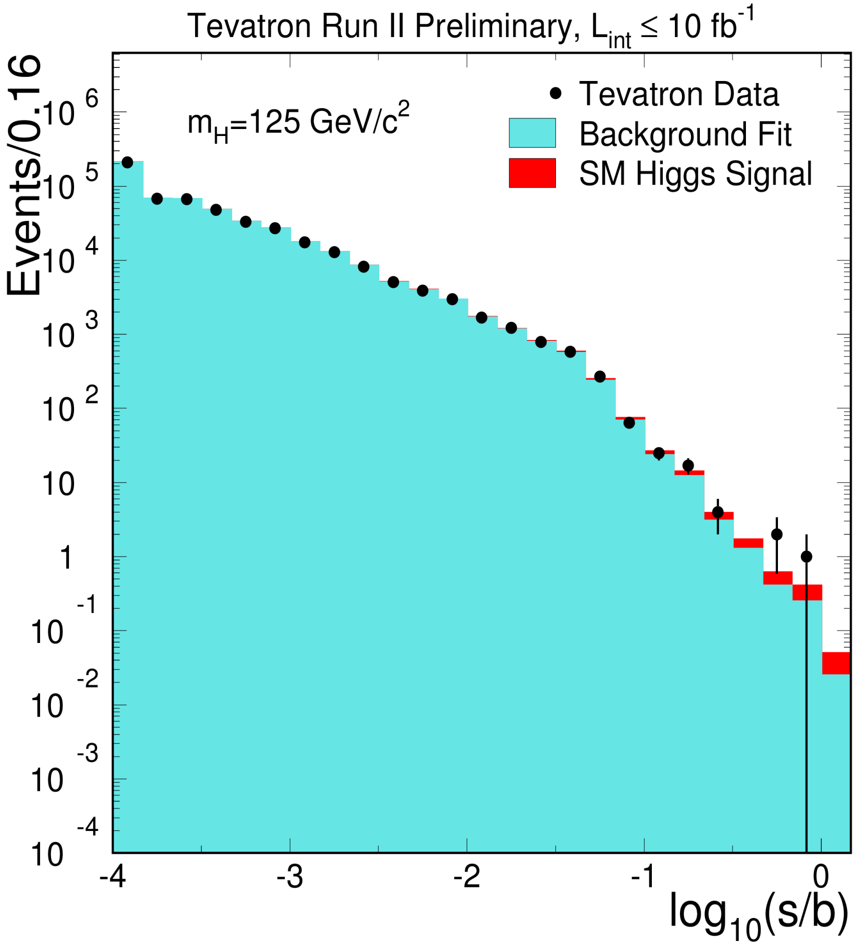
- In order to combine searches in many different production/decays, cross section limits are given with respect to nominal SM predictions.
- This requires to incorporate latest theoretical predictions and careful treatment of systematic, correlations cross channels & experiments.
  - –Luminosity (6%), trigger and lepton ID(2-5%)
  - –B-tagging (3.9-7.8%) and mistag (10-20%)
  - –Jet energy scale (JES) shape and rate
  - –Theoretical uncertainties (PDF, Q2, ISR/FSR)
  - –W/Z + jets modeling
- Interpreting data using Bayesian and Cls statistical tools to set limits or measure the production cross section.
- Most systematic parameters are constrained by the data in the background dominated region.

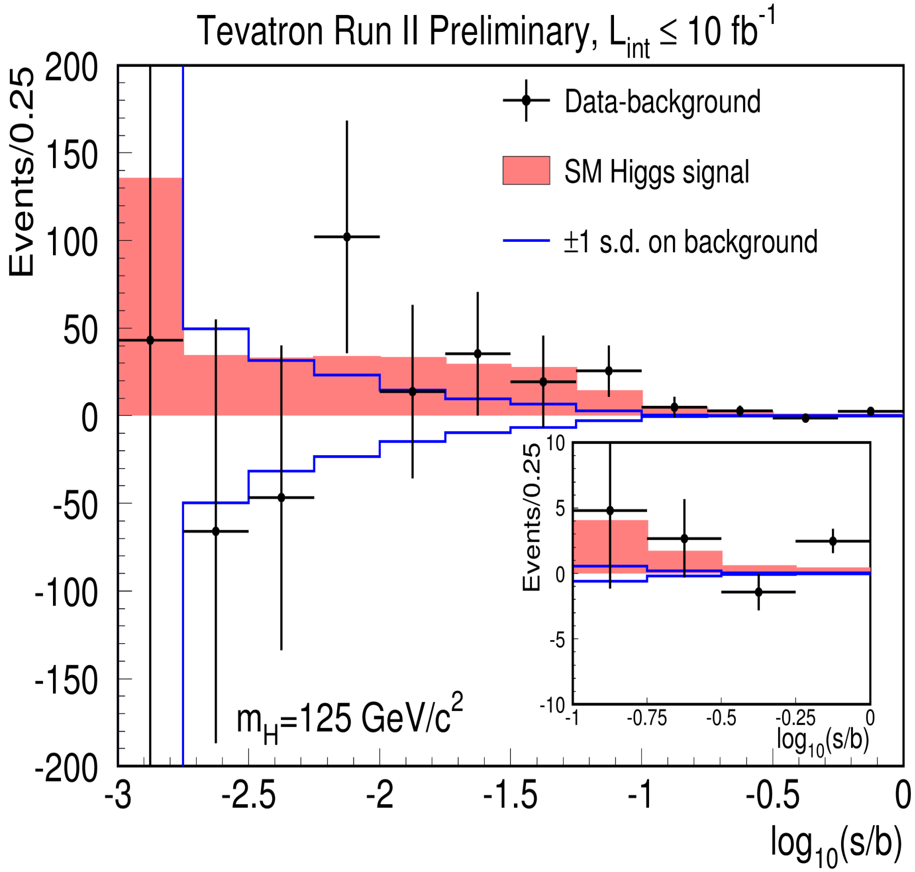
# List of Input Channels

| DØ | Luminosity ($fb^{-1}$) | $M_H$ (GeV) | Reference |
|---|---|---|---|
| $WH \to \ell\nu bb$ | 9.7 | 90–150 | Phys. Rev. Lett. 109, 121804 (2012); Sub to PRD arXiv:1301.6122 |
| $ZH \to \ell\ell b\bar{b}$ | 9.7 | 90–150 | Phys. Rev. Lett. 109, 121803 (2012) |
| $ZH \to \nu\bar{\nu}b\bar{b}$ | 9.5 | 100–150 | Phys. Lett. B 716, 285 (2012) |
| $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ | 9.7 | 100–200 | Acc to PRD arXiv:1301.1243 |
| $H + X \to WW \to \mu^\pm\tau_h^\mp + \leq 1\text{jet}$ | 7.3 | 155–200 | Phys. Lett. B 714, 237 (2012) |
| $H \to W^+W^- \to \ell\nu q'\bar{q}$ | 9.7 | 100–200 | Sub to PRD arXiv:1301.6122 |
| $VH \to ee\mu/\mu\mu e{+}X$ | 9.7 | 100–200 | Sub to PRD arXiv:1302.5723 |
| $VH \to e^\pm\mu^\pm{+}X$ | 9.7 | 100–200 | Sub to PRD arXiv:1302.5723 |
| $VH \to \ell\nu q'\bar{q}q'\bar{q}$ | 9.7 | 100–200 | Sub to PRD arXiv:1301.6122 |
| $VH \to \tau_h\tau_h\mu + X$ | 8.6 | 100–150 | Sub to PRD arXiv:1302.5723 |
| $H + X \to \ell\tau_h jj$ | 9.7 | 105–150 | Acc. by PRD arXiv:1211.6993 |
| $H \to \gamma\gamma$ | 9.7 | 100–150 | Submitted to PRD, arXiv:1301.5358 |
| CDF | | | |
| $WH \to \ell\nu bb$ | 9.45 | 90–150 | Phys. Rev. Lett. 109, 111804 (2012) |
| $ZH \to \ell\ell b\bar{b}$ | 9.45 | 90–150 | Phys. Rev. Lett. 109, 111803 (2012) |
| $ZH \to \nu\bar{\nu}b\bar{b}$ | 9.45 | 90–150 | Phys. Rev. Lett. 109, 111805 (2012); Acc. by PRD arXiv: 1301.4440 |
| $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ | 9.7 | 110–200 | FERMILAB-PUB-13-029-E, For submission to PRD |
| $H \to WW \to e\tau_h\mu\tau_h$ | 9.7 | 130–200 | FERMILAB-PUB-13-029-E, For submission to PRD |
| $VH \to ee\mu/\mu\mu e{+}X$ | 9.7 | 110–200 | FERMILAB-PUB-13-029-E, For submission to PRD |
| $H \to ZZ \to llll$ | 9.7 | 120–200 | Phys. Rev. D 86 (2012) 072012 |
| $H \to \tau\tau$ | 6.0 | 100–150 | Phys. Rev. Lett. 108, 181804 (2012) |
| $VH \to jjb\bar{b}$ | 9.45 | 100–150 | JHEP 1302 (2013) 004 |
| $H \to \gamma\gamma$ | 10.0 | 100–150 | Phys. Lett. B 717, 173 (2012) |
| $t\bar{t}H \to WWb\bar{b}b\bar{b}$ | 9.45 | 100–150 | Phys. Rev. Lett. 109 (2012) 181802 |

# Visualizing Data at $M_H$=125 GeV

- Display cumulative discriminant from >100 channels, ordered by S/B.
- Expect to find an excess in high score region if there is a  signal.

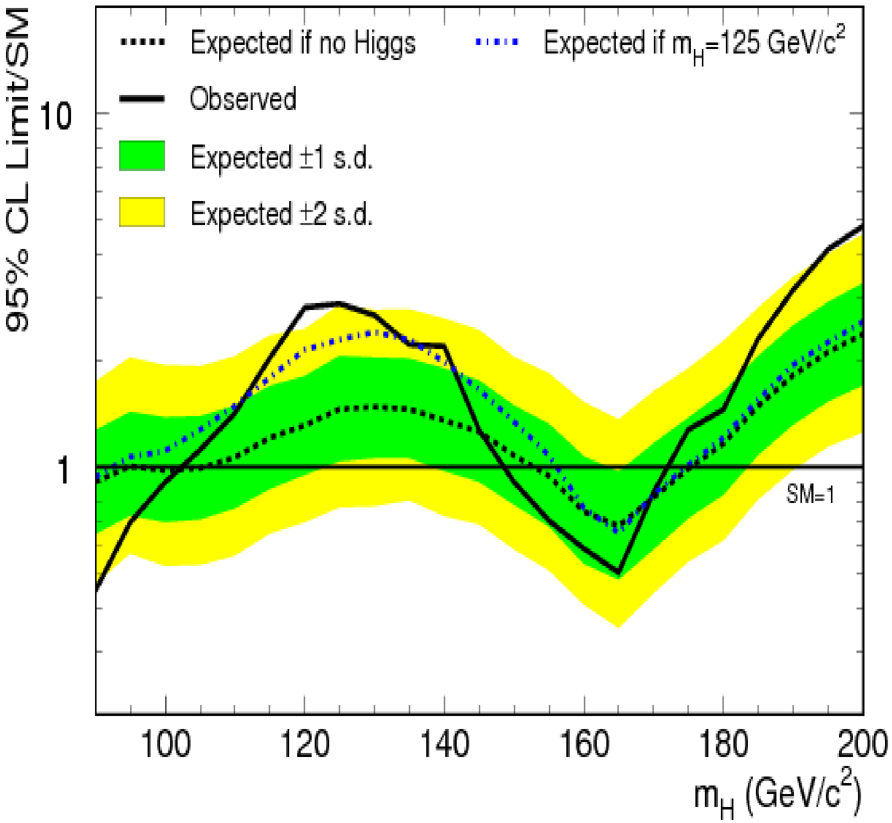


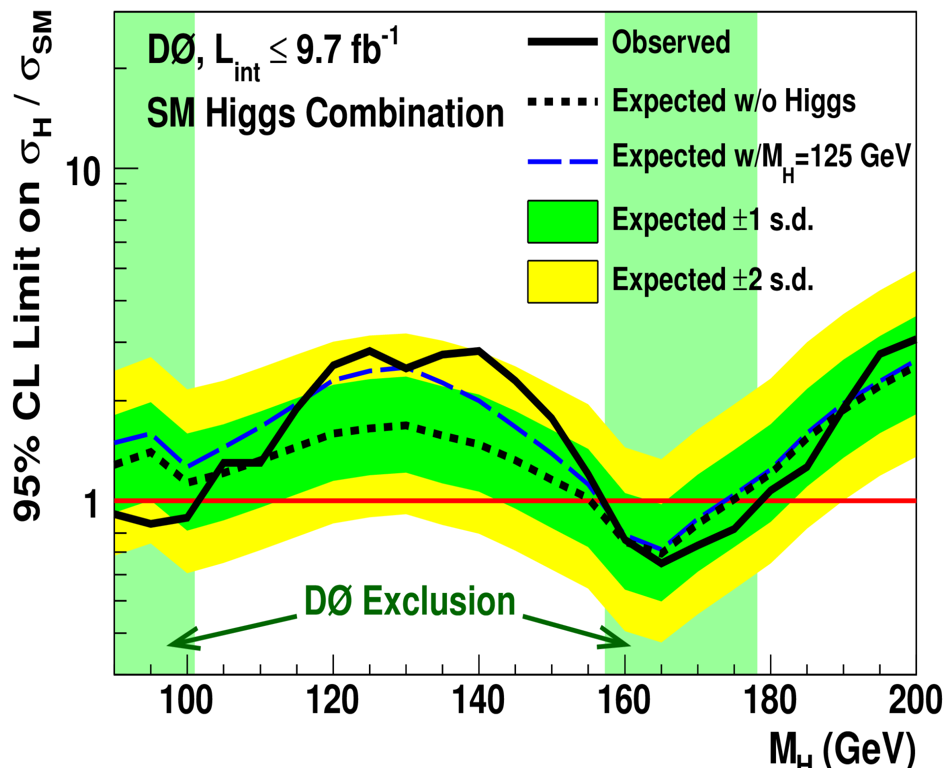



# What's new

- There are no major changes in the analyses since HCP2012.
- Both collaboration have done many checks and all results have been submitted to the publication.
- The final Tevatron paper has been accepted by PRD recently.

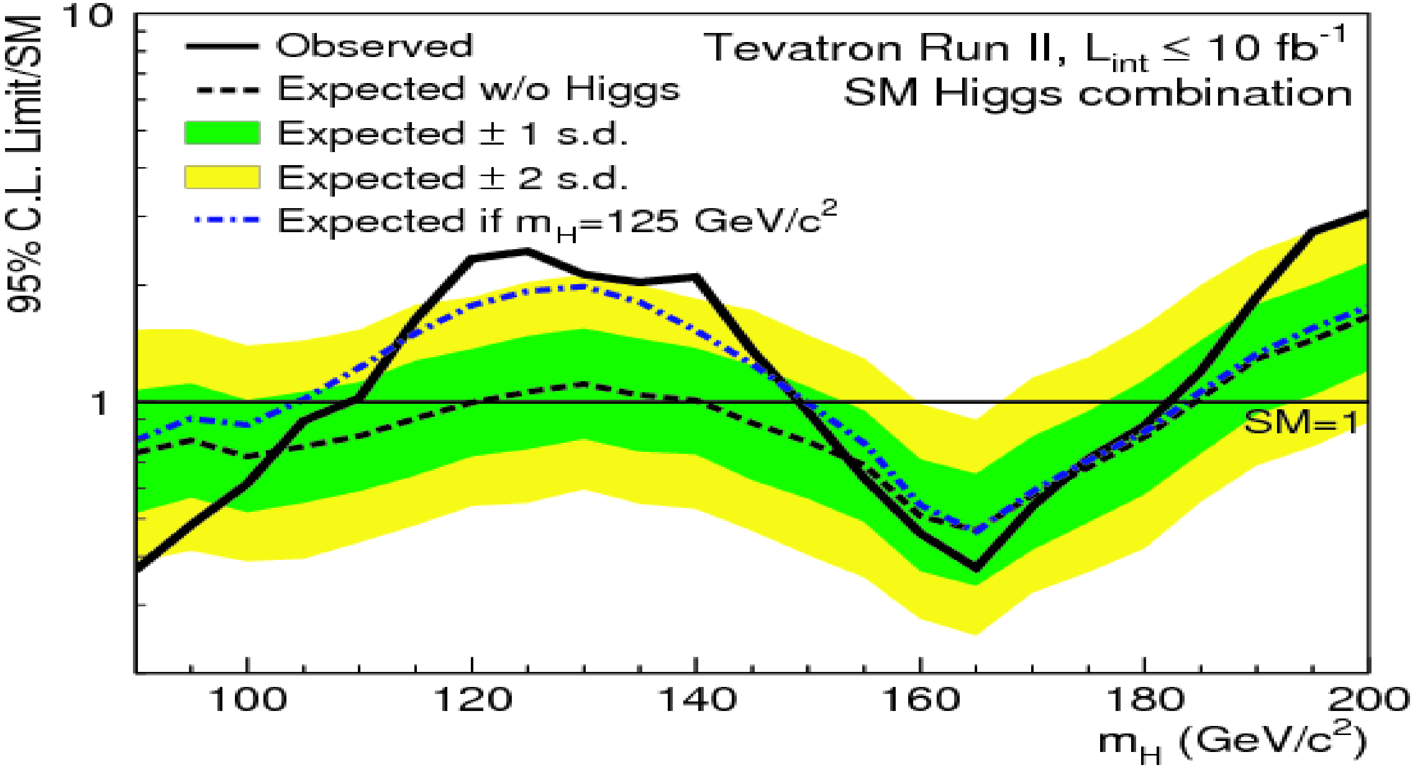
CDF with 10 fb$^{-1}$



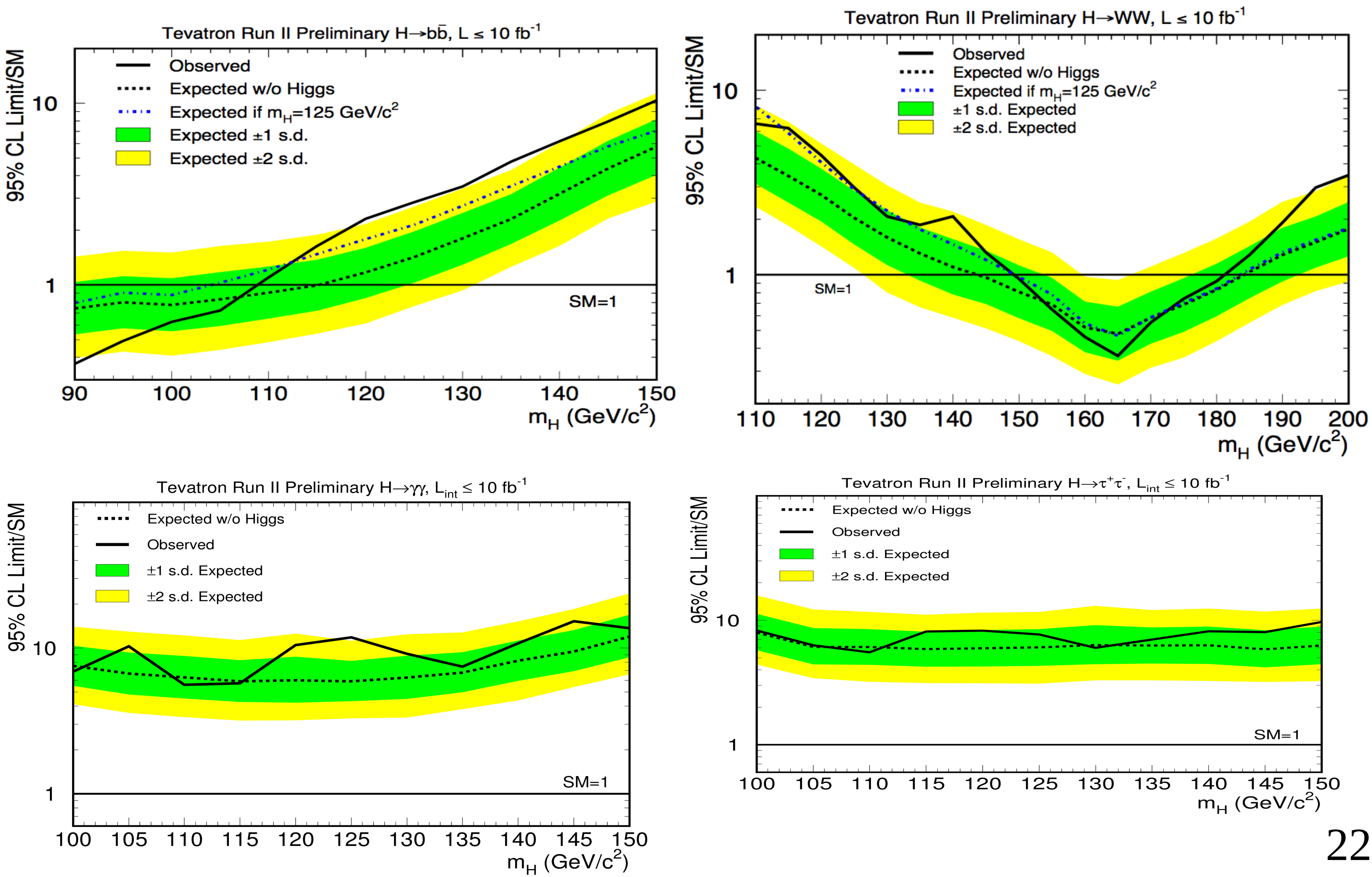



# Tevatron Combination

- Exclusion regions at 95% CL:
  - High mass: 149-182 with exp. of 140-184 GeV/$c^2$
  - Low mass: 90-107 with exp. of 90-121 GeV/$c^2$.
- Broad excess(>2σ) observed between 115-140 GeV/$c^2$.

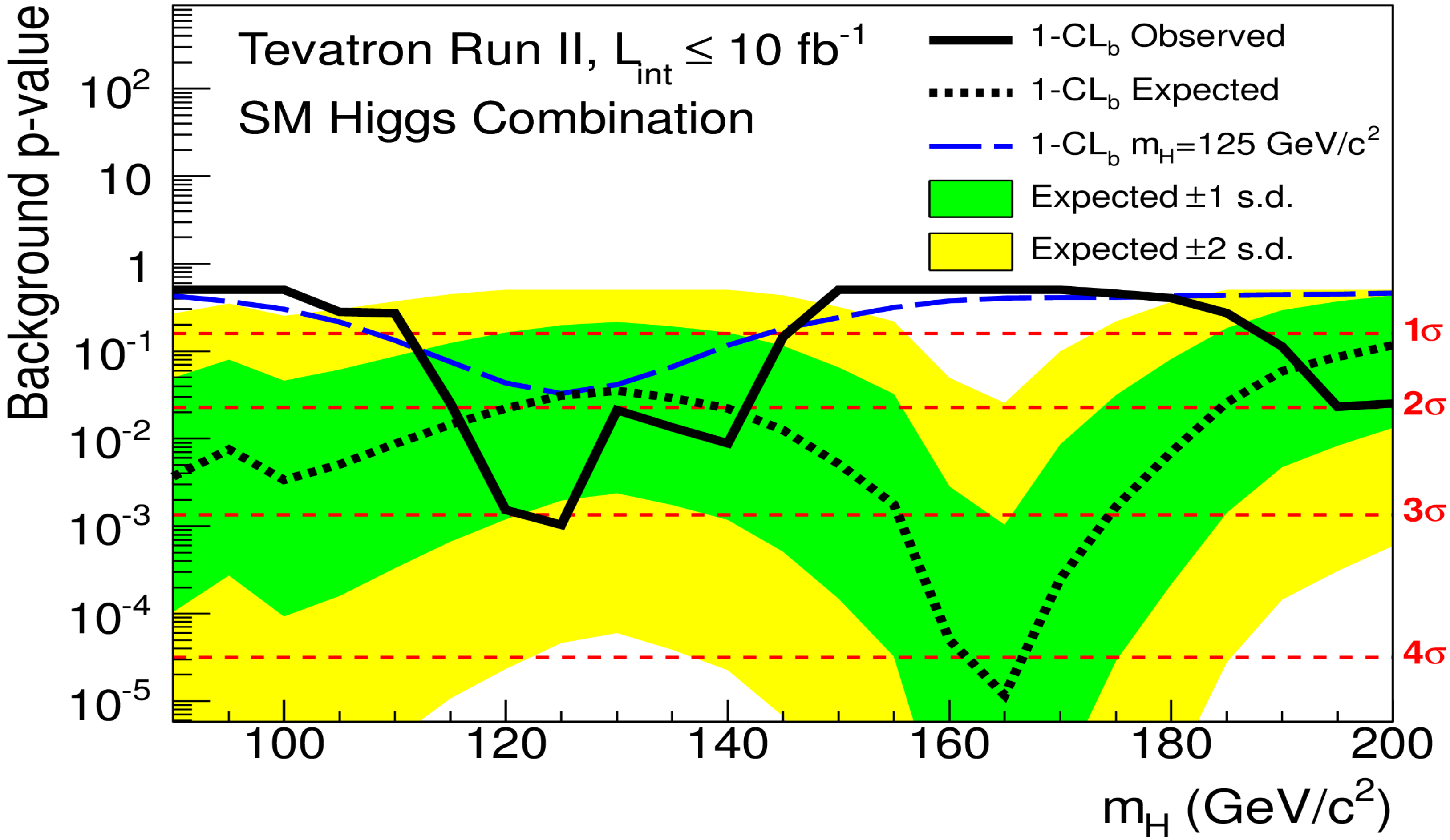


# Tevatron Combination by Channel



# Quantifying the Excess

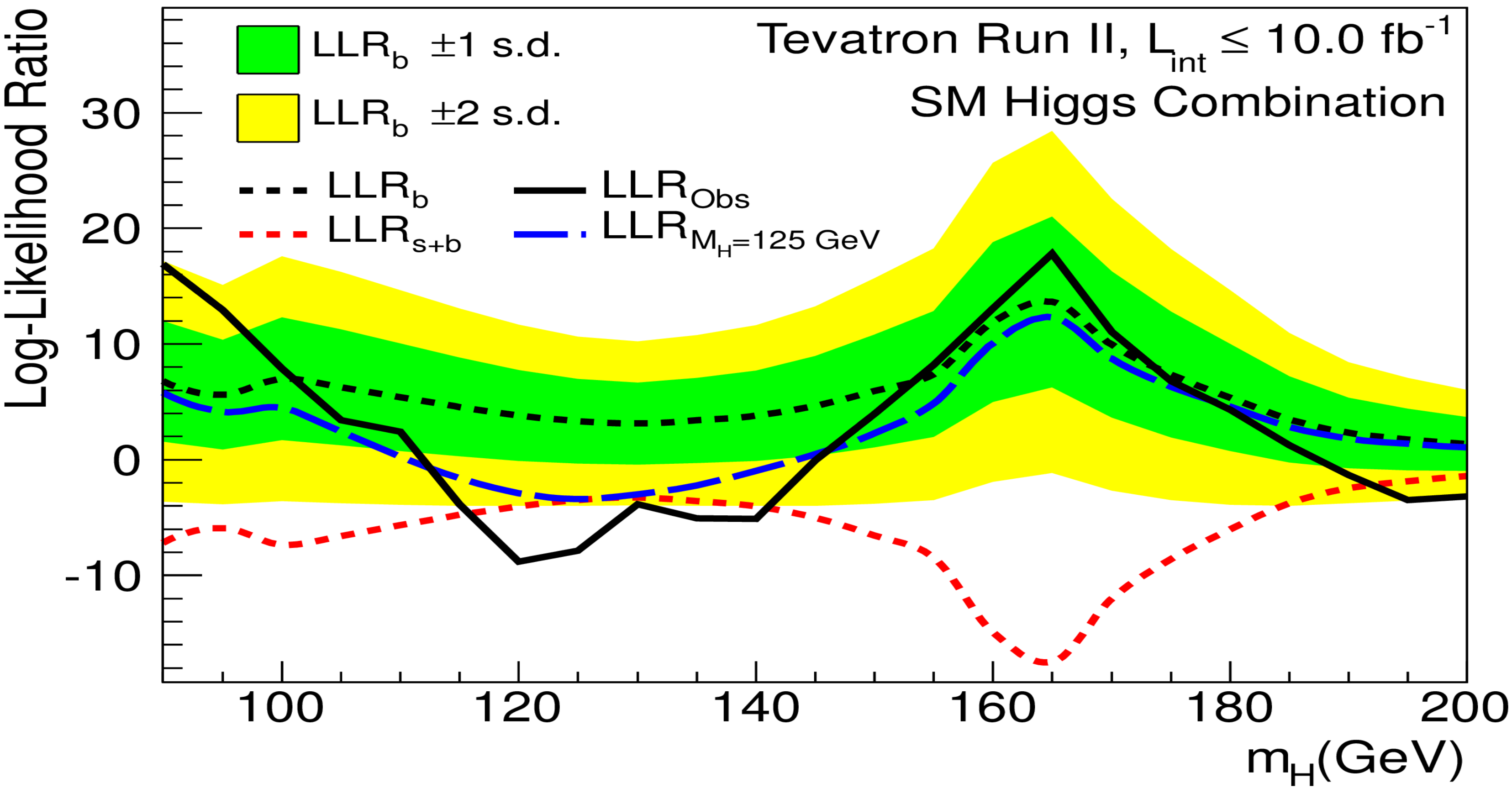
- Calculating local p-value for background-only hypothesis.
- The minimum p-value is found to be 3.1σ at $m_H$ =125GeV.



# Compatible with SM Higgs at 125 GeV

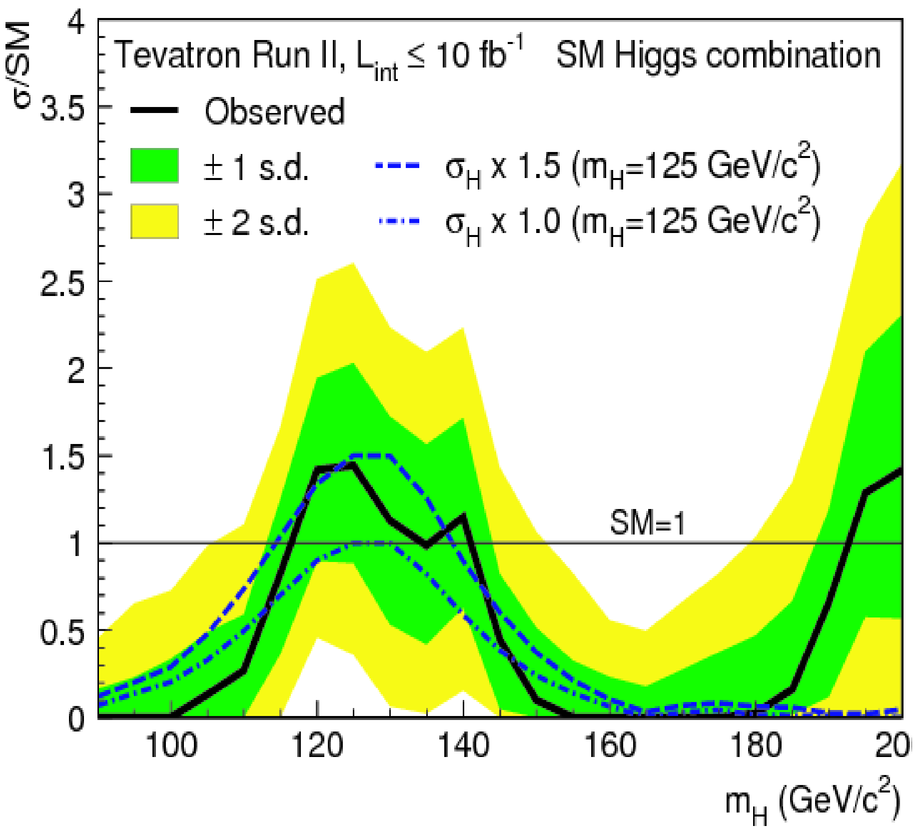
- Compared LLR by injecting a signal of 125 to backgrnd pesudo-experiments. The distribution is broad due to MVA not optimized for mass, but for S/B.

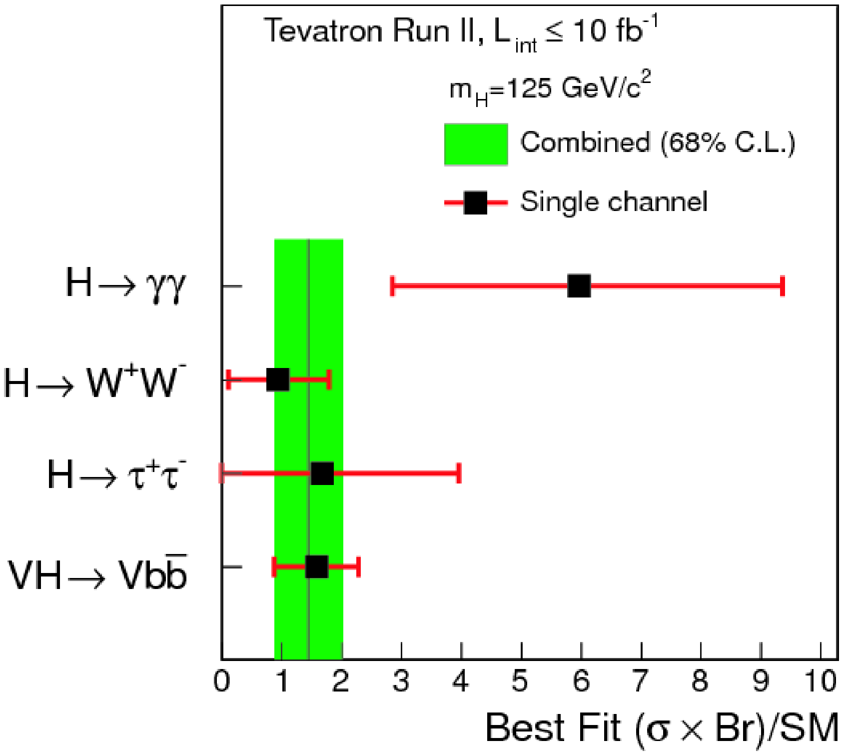
- The shape including a 125 GeV Higgs is consistent with observed in the data.



# Tevatron Cross Section Fits

- The fitted signal strength is (1.4±0.6) @125 GeV, consistent with SM prediction.
- Separate fits to $H \rightarrow \gamma\gamma$, WW, $\tau\tau$, bb, consistent across channels.



# Studies of Higgs Boson Properties

- Studies of the coupling will help to understand what the new particle is and they can be parameterized through coupling factors respect to SM:
  - $K_f$ is for Hff fermion coupling,
  - $K_W$, $K_Z$, $K_V$ for HWW, HZZ, HVV boson coupling ( $\lambda_{WZ}=K_W/K_Z$).

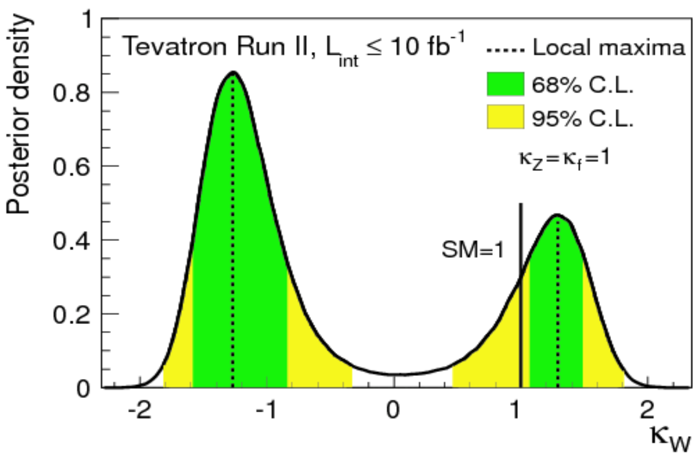
- Most searches at the Tevatron are sensitive to the product of fermion and boson couplings , for example:
  - $\mu^{ggH}{}_{vv}=\sigma(gg\rightarrow H)*B(H\rightarrow VV)/(\sigma*B)_{SM}=(0.95K_f^2+0.05K_fK_V) * K_V^2$ .
  - $\mu^{VH}{}_{bb}=\sigma(VH)*B(H\rightarrow bb)/(\sigma*B)_{SM} =K_V^2 * K_f^2$.

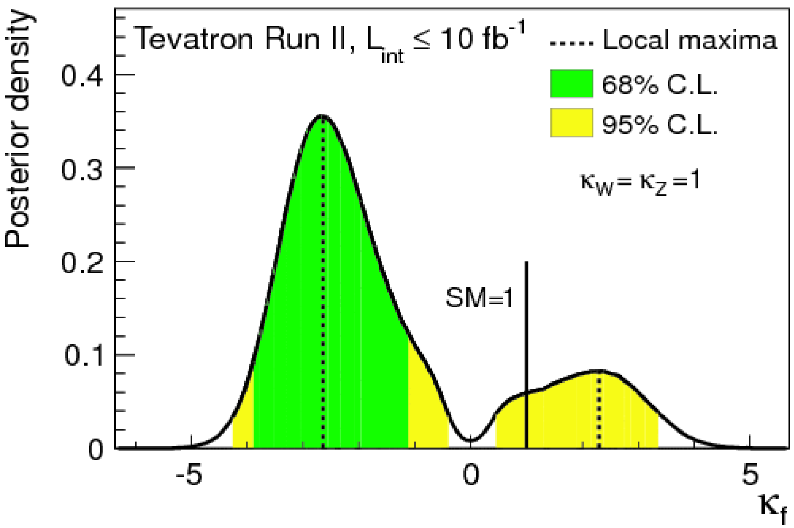
- We follow the procedures of LHC Higgs cross section WG (arXiv:1209.0040).

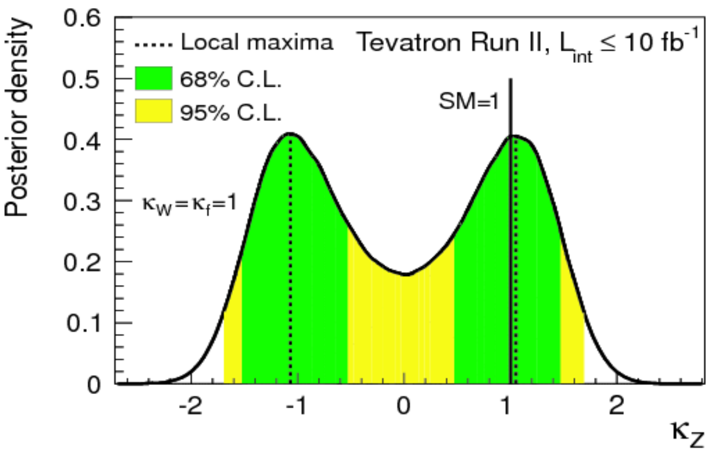
- Assuming uniform prior for all K's.

# 1-D Higgs Boson Coupling

- Vary $K_W$, $K_Z$ and $K_f$ independently and measure each coupling:
- Results are consistent with SM predictions.



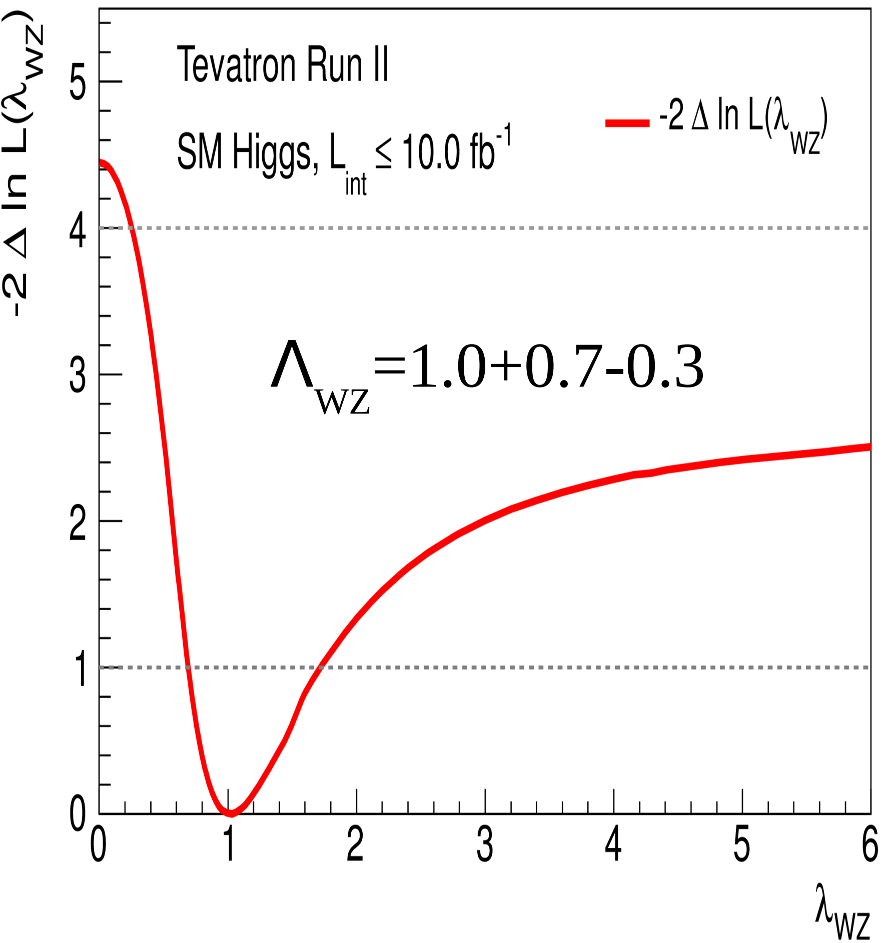



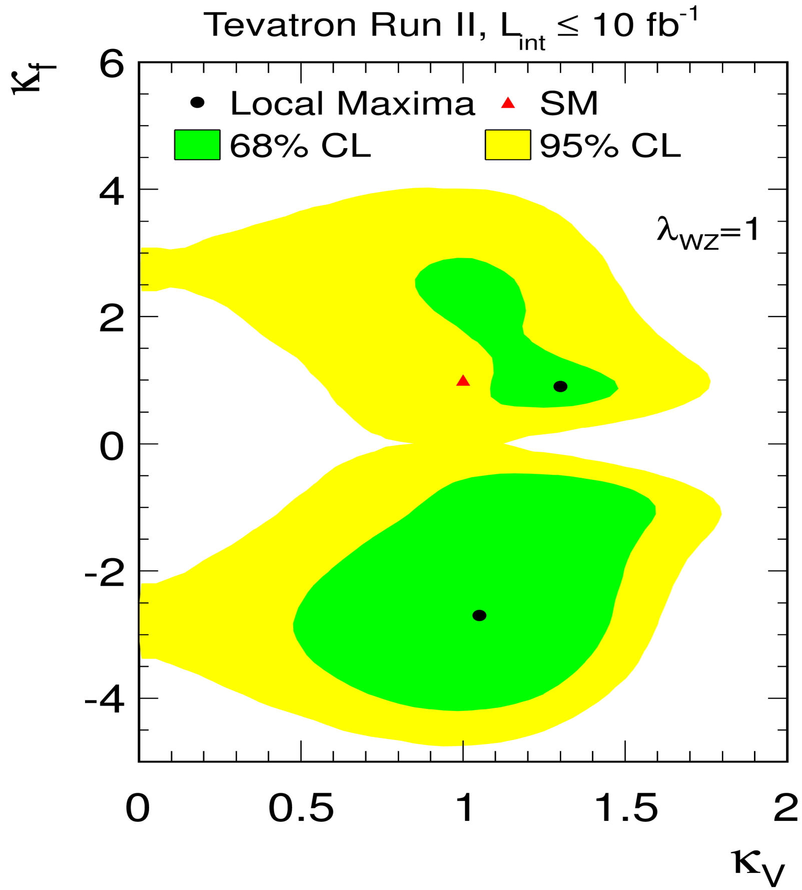




- $K_Z$ =+-(1.05+0.45-0.55)
- $K_f$ = -2.64 +1.59-1.30
- $K_W$ = -1.27+0.46-0.29 or [1.04,1.51]
- Negative values of $K_W$ and $K_f$ are preferred due to $H\rightarrow\gamma\gamma$ excess

# Constraining Higgs Boson Coupling

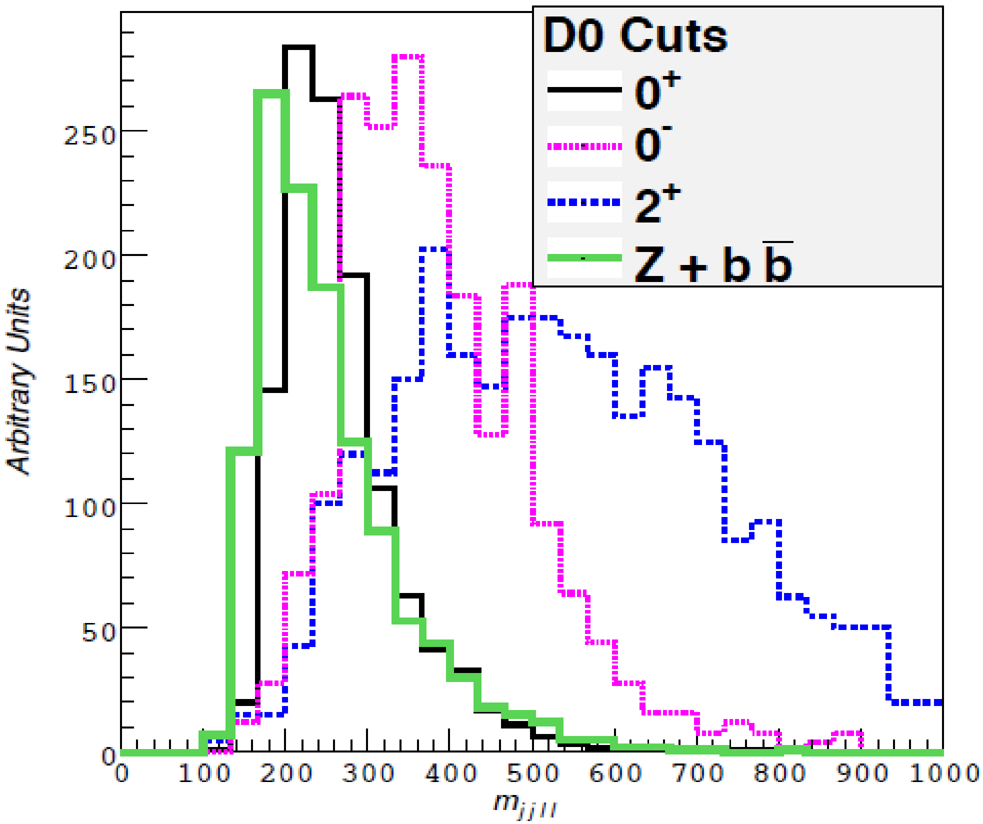
- Constraining custodial symmetry: $\lambda_{WZ}=K_W/K_Z$ by assuming $K_f=1$
- Constraining $K_f$ and $K_V$ simultaneously by assuming $\lambda_{WZ} = 1$.
- Results are consistent with SM predictions.

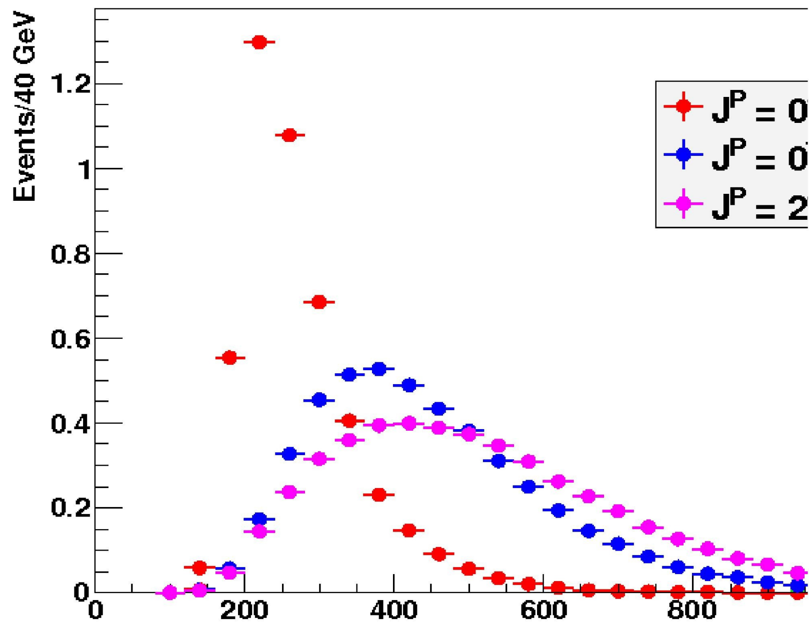


# New Higgs Spin Measurement from D0

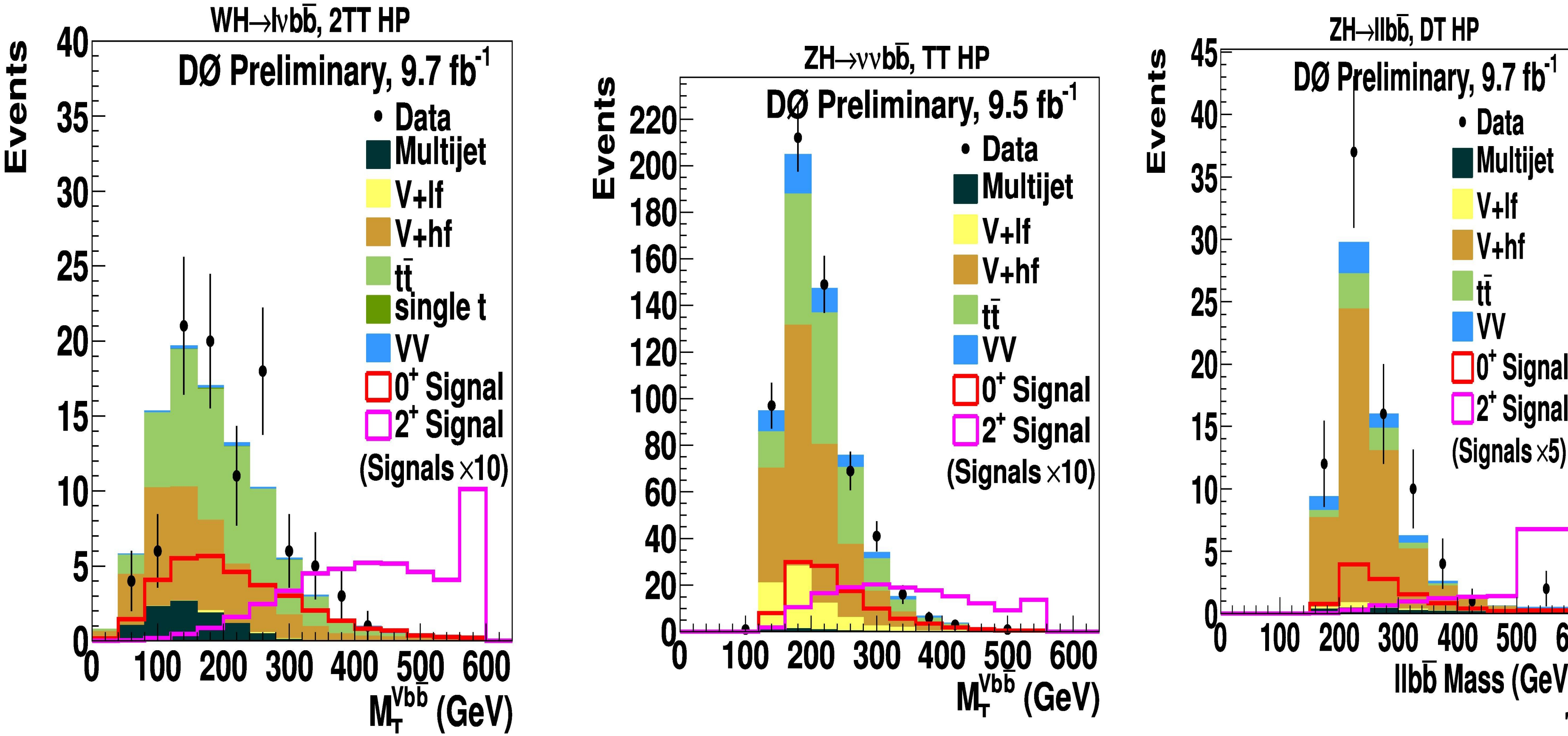
- SM predicts Higgs JP=$0^+$, but $0^-$ and $2^+$ possible
- LHC confirms $0^+$ with bosonic decay modes
- Tevatron sensitive in VH final states where invariant mass of VH depends on $J^P$ assignment, Ellis et al. JHEP 1211 134(2012).



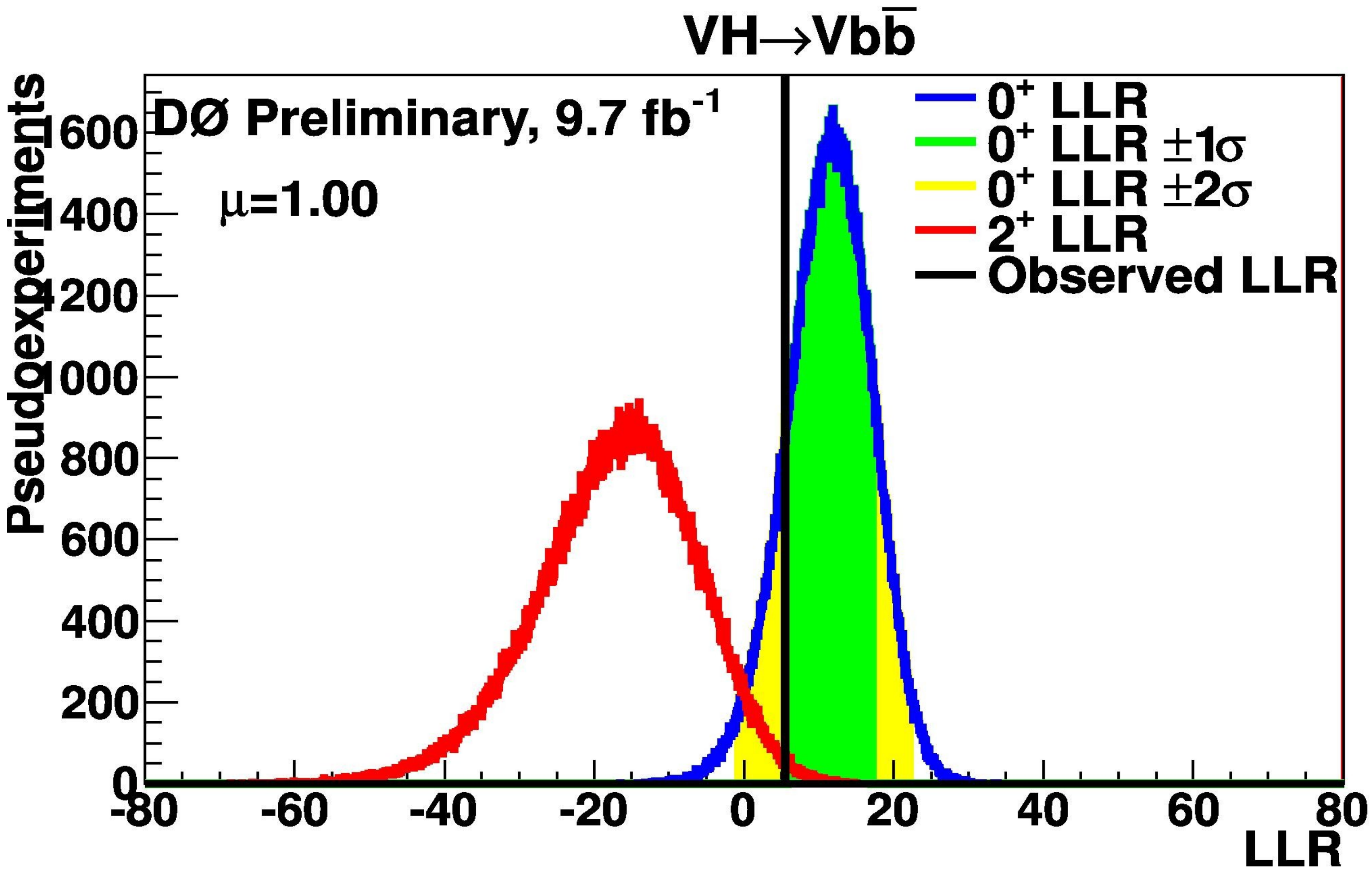
# Spin Strategy

- Re-use published VH→Vbb analyses with same selections
- Use RS graviton as $2^+$ from madgraph, normalized to $(\sigma x B)_{SM}$.
- Use dijet mass or SM MVA to improve s/b
- Fit the final discriminate VH visible mass.



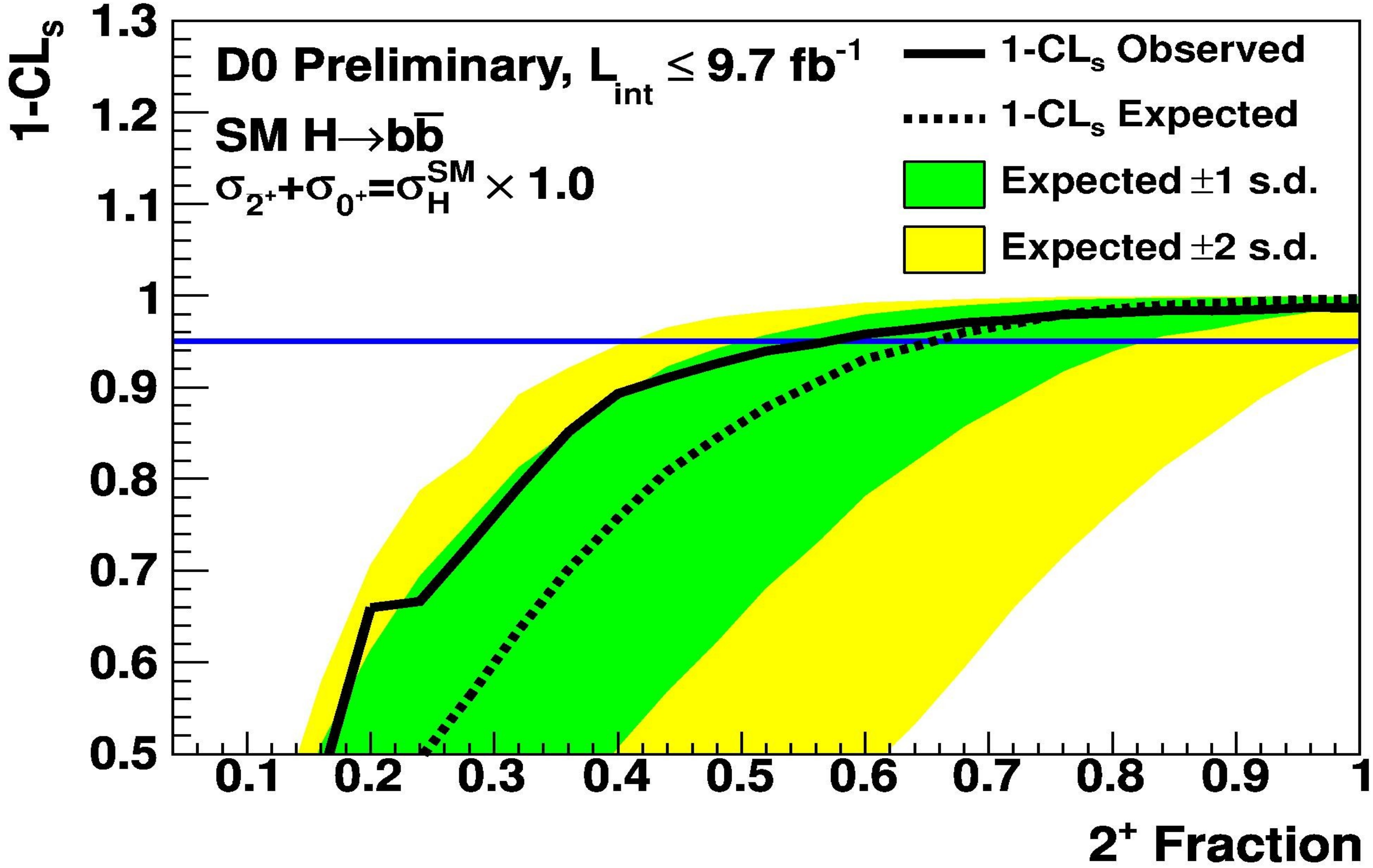
# Spin Results

- Test LLR=-2log(L($2^+$)/L($0^+$)) assuming μ=1.
- $2^+$ is excluded at 99.2% (exp. 99.95%)CL with μ=1 in the data.



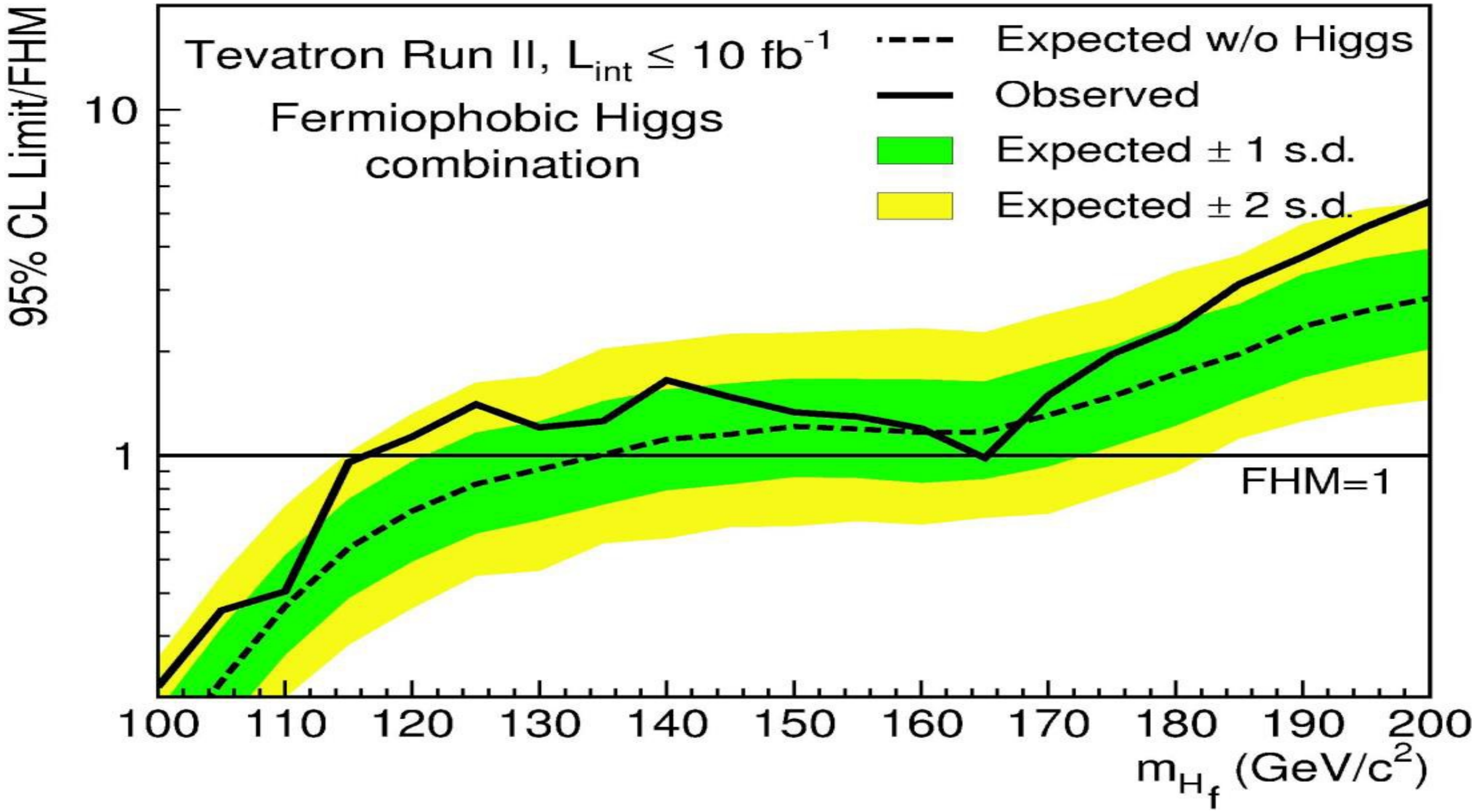
# Spin Results

- Consider both $2^+$ and $0^+$ signal in data
- Vary fraction of $2^+$ from 0 to 1
- Excluding at 95% CL: $f_{2+}$>0.56 (exp. 0.65) for μ=1.0
- Work is on going to combine with CDF data.



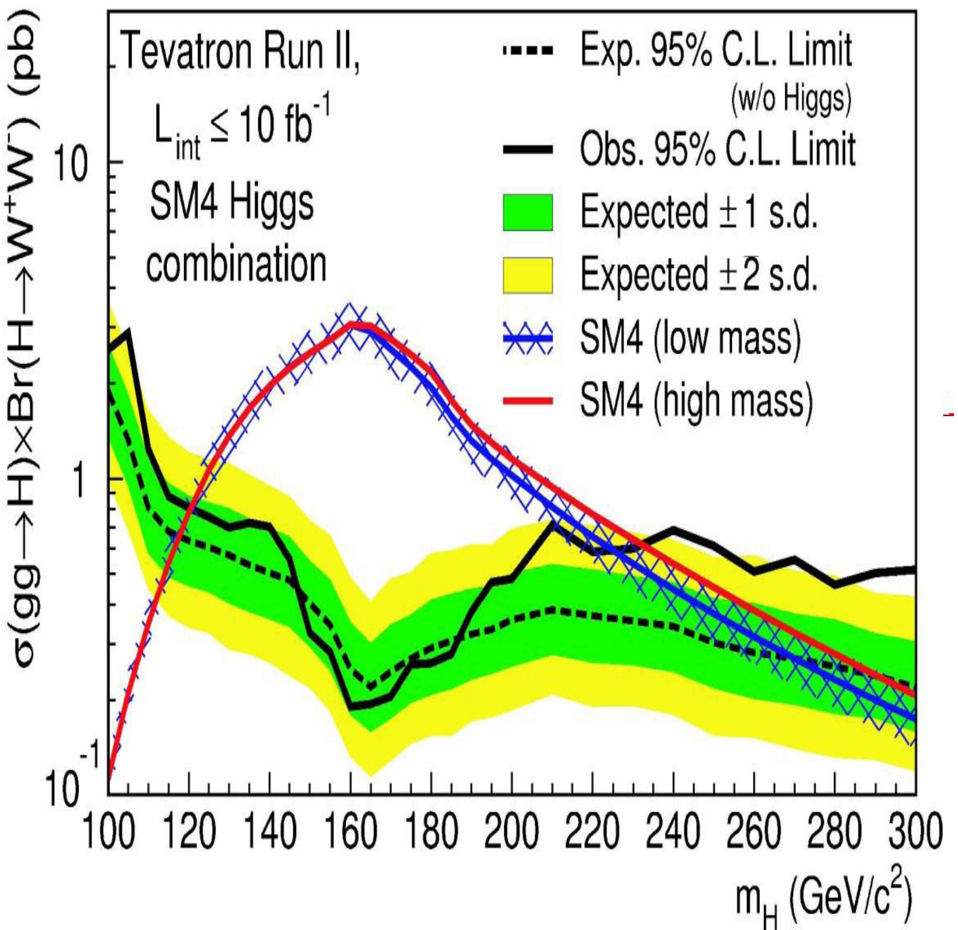
# Fermiophobic Higgs Search

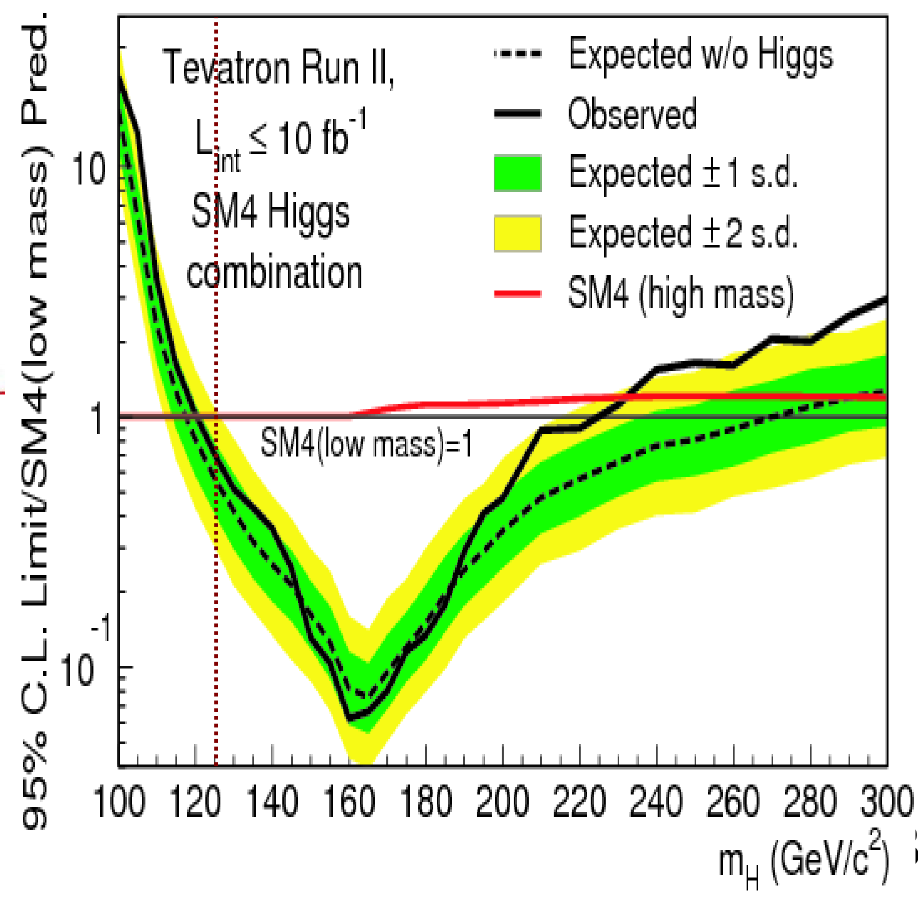
- Couplings to fermions highly suppressed
- Only VH and VBF production, a large enhancement in B(H→γγ).
- Exclusion at 95% CL: obs. (100,116) with exp. (100,135) GeV



# $4^{th}$ Generation Quark Search

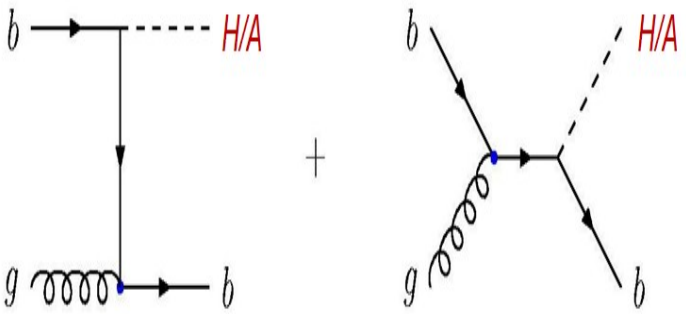
- A sequential $4^{th}$ generation of fermions could enhance ggH coupling by a factor 3 while providing new source of CP violation to explain matter-antimatter asymmetry.
- $4^{th}$ gen. hypothesis seems excluded for observed $m_H$=125 GeV.

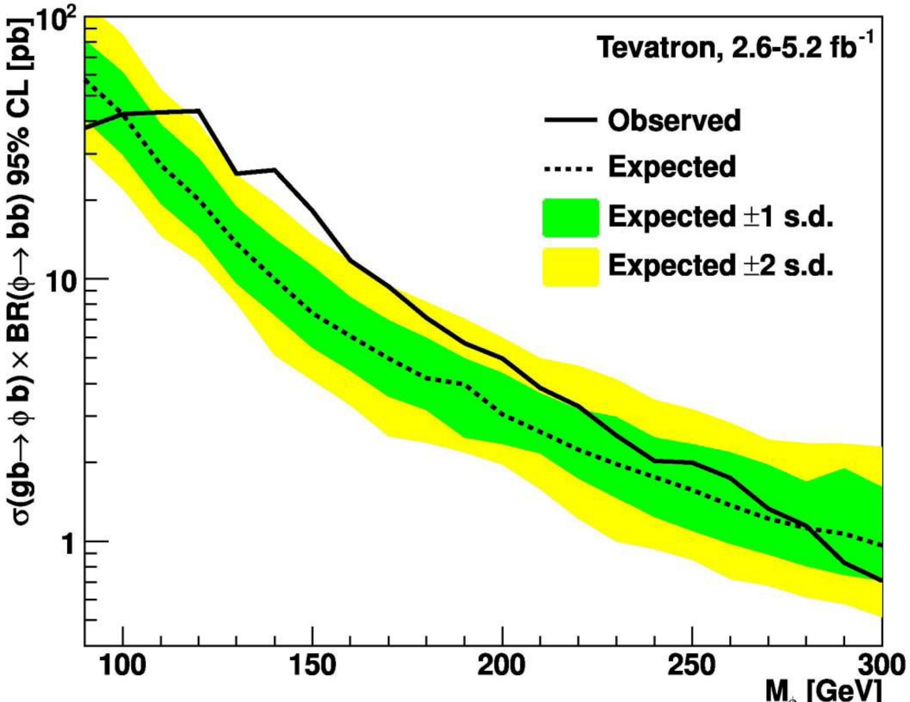


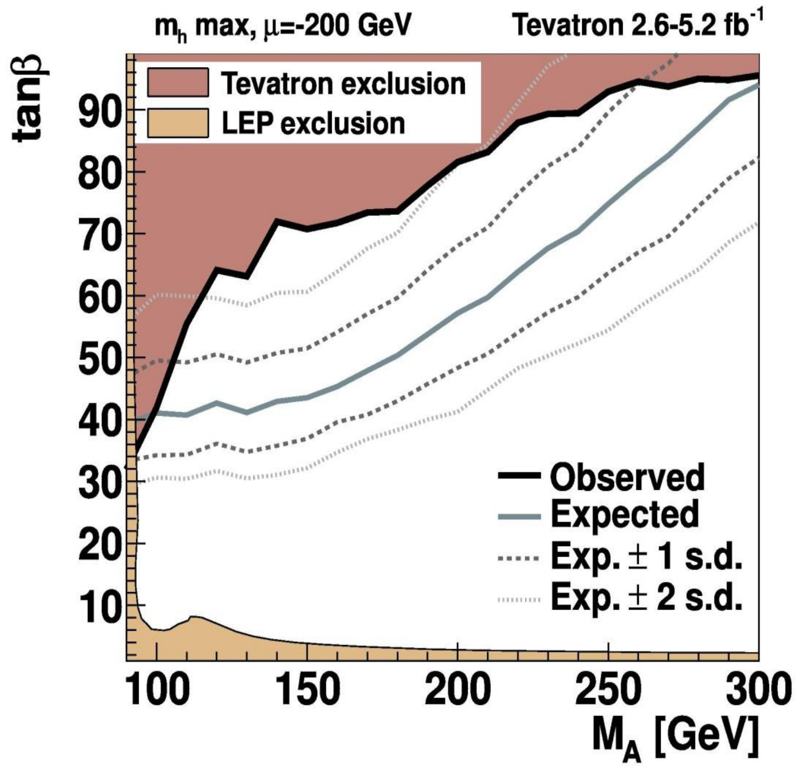



# MSSM Higgs Search at the Tevatron

- MSSM Higgs production is enhanced by $\tan\beta^2$ in association with b-quarks and decaying in $H/A \to bb$.
- Mass reconstruction is challenging with multi-b quark final state.
- Some excess observed at $m_H$=145 GeV .



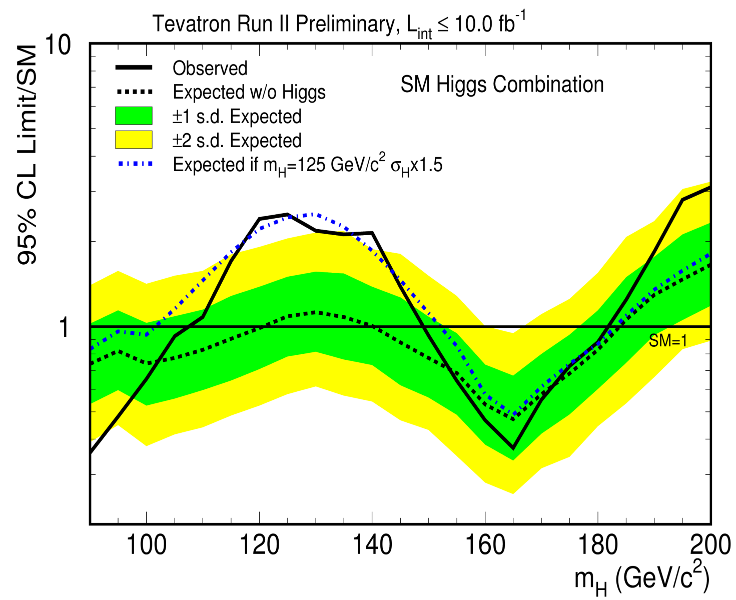
# Conclusion

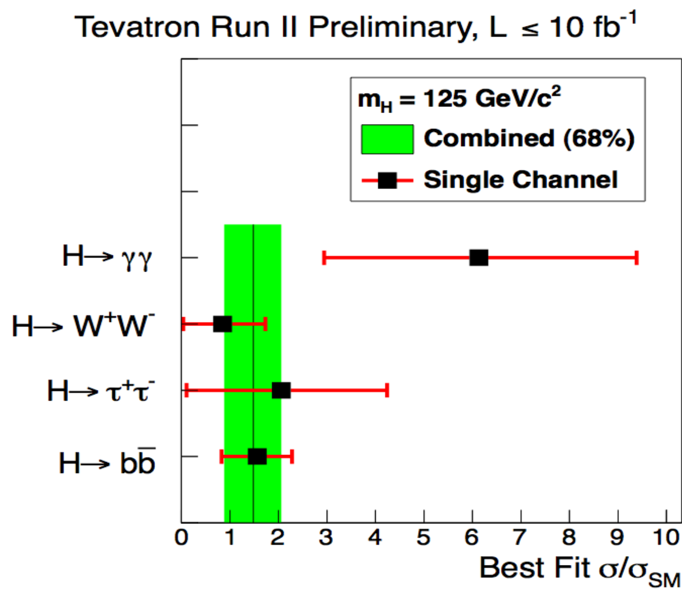
•Latest Tevatron results are presented based on full Run II dataset.

•Tevatron has achieved SM sensitivity over its expected accessible mass region(90-190 GeV).

• Observed a broad excess in $115 < M_H < 140$ GeV relative to bckgrnd-only hypothesis with a local p-value of $3.1\sigma$ consistent with LHC discovery.

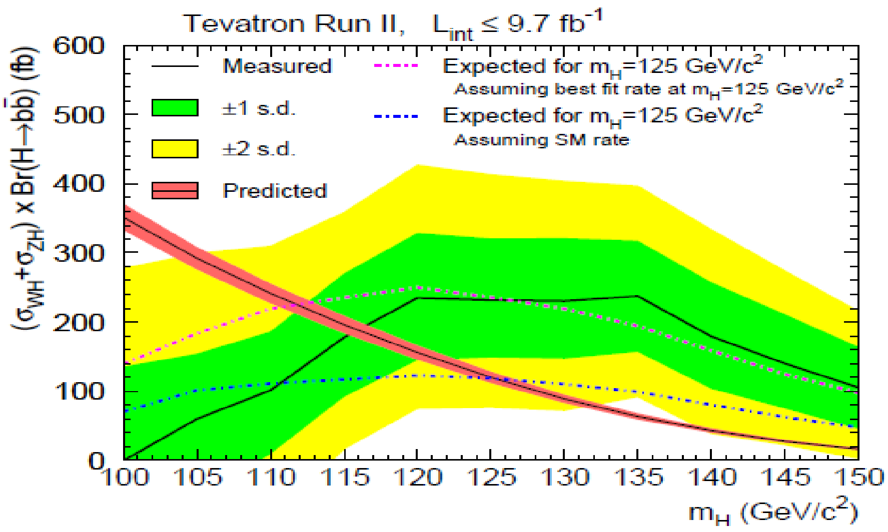
•Studies of Higgs boson coupling at Tevatron are consistent with SM prediction and provide complementary information to LHC.

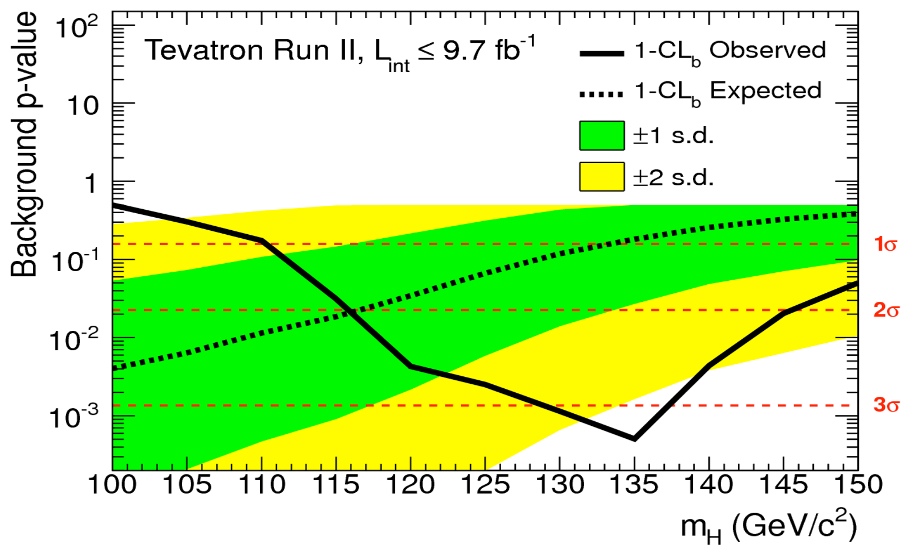


# BACKUP

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




- Last Summer:
  - $\sigma_{VH}$=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:
  - $\sigma_{VH}$=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.