Higgs Boson Searches at the Tevatron

Erich W. Varnes
University of Arizona
for the CDF and DØ Collaborations

32nd International Symposium on Physics in Collision
Štrbské Pleso, Slovakia
September 15, 2012

Outline

- Introduction
  - Current Status
  - Search Strategy
- Searches for SM Higgs at high mass
- Searches for SM Higgs at low mass
- Combinations
- Searches for non-SM Higgs

Current Status

- The status of the Higgs search changed dramatically this summer

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

Phys. Lett. B 716, 1 (2012)

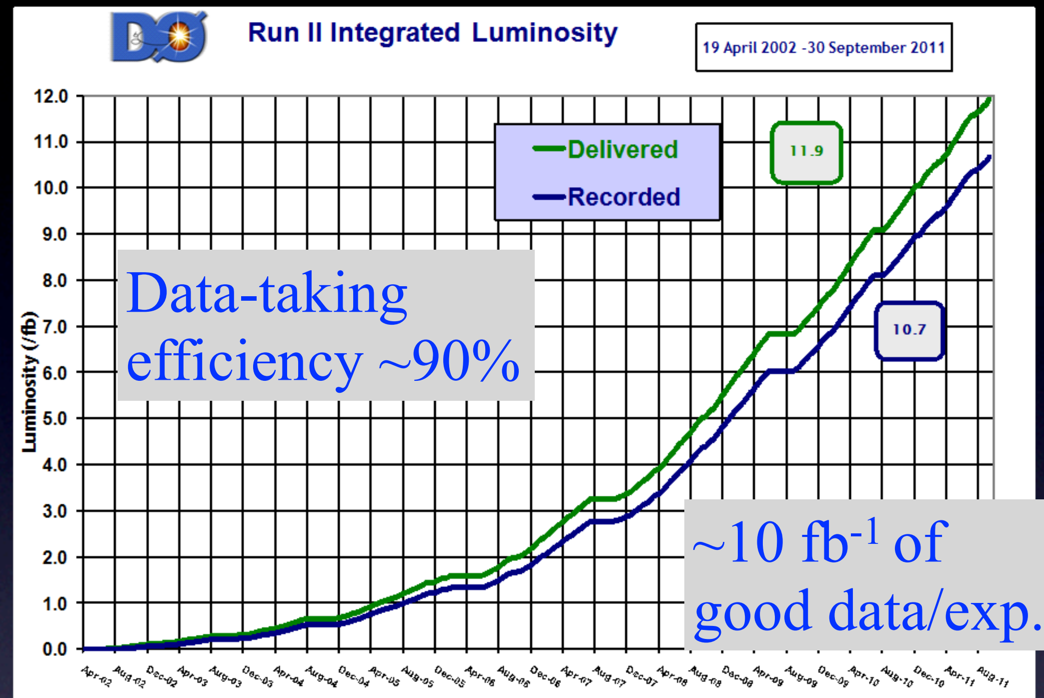
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

Phys. Lett. B 716, 30 (2012)

- Congratulations to ATLAS, CMS, and the LHC!
- Can we still learn something from the Tevatron?

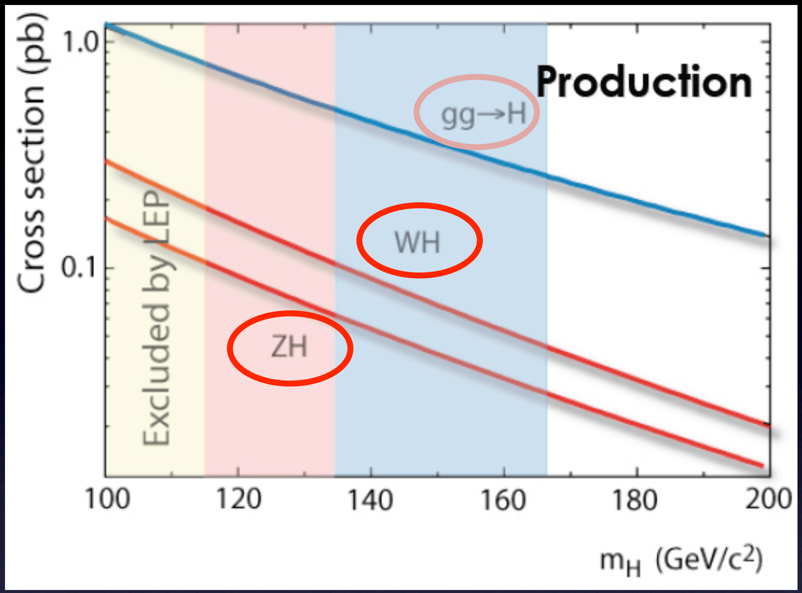
Tevatron

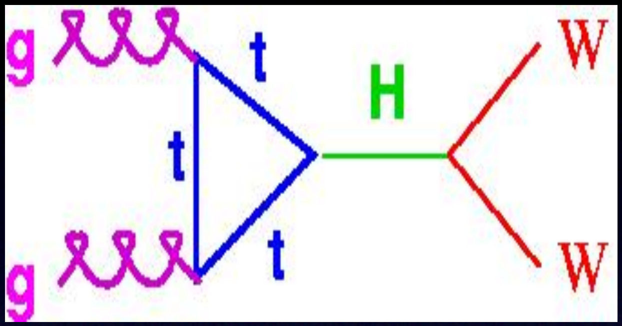


- Data-taking stopped in September 2011
  - but ideas kept on coming!
  - latest results are ~10-20% more sensitive than initial reports using the full data sample

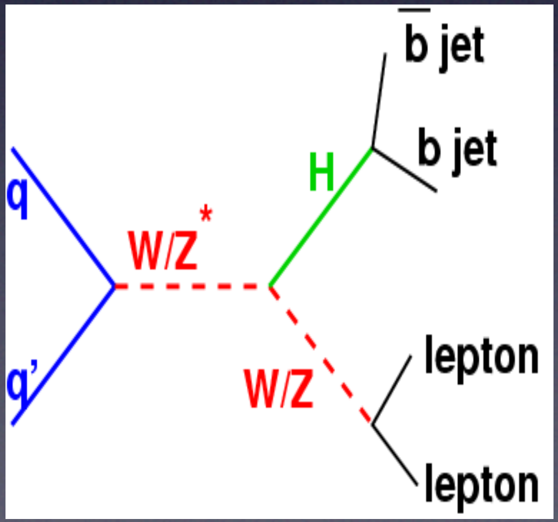
Higgs Production and Decay

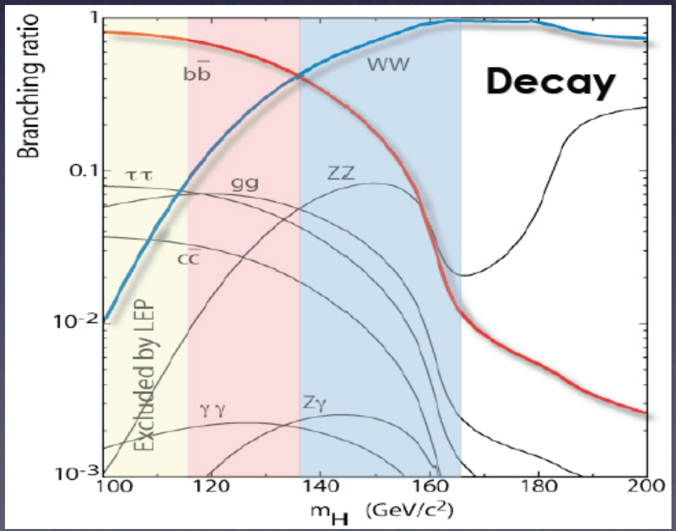
- There are two main production modes at the Tevatron:





- At ~125 GeV, the main decay mode is to $b\bar{b}$





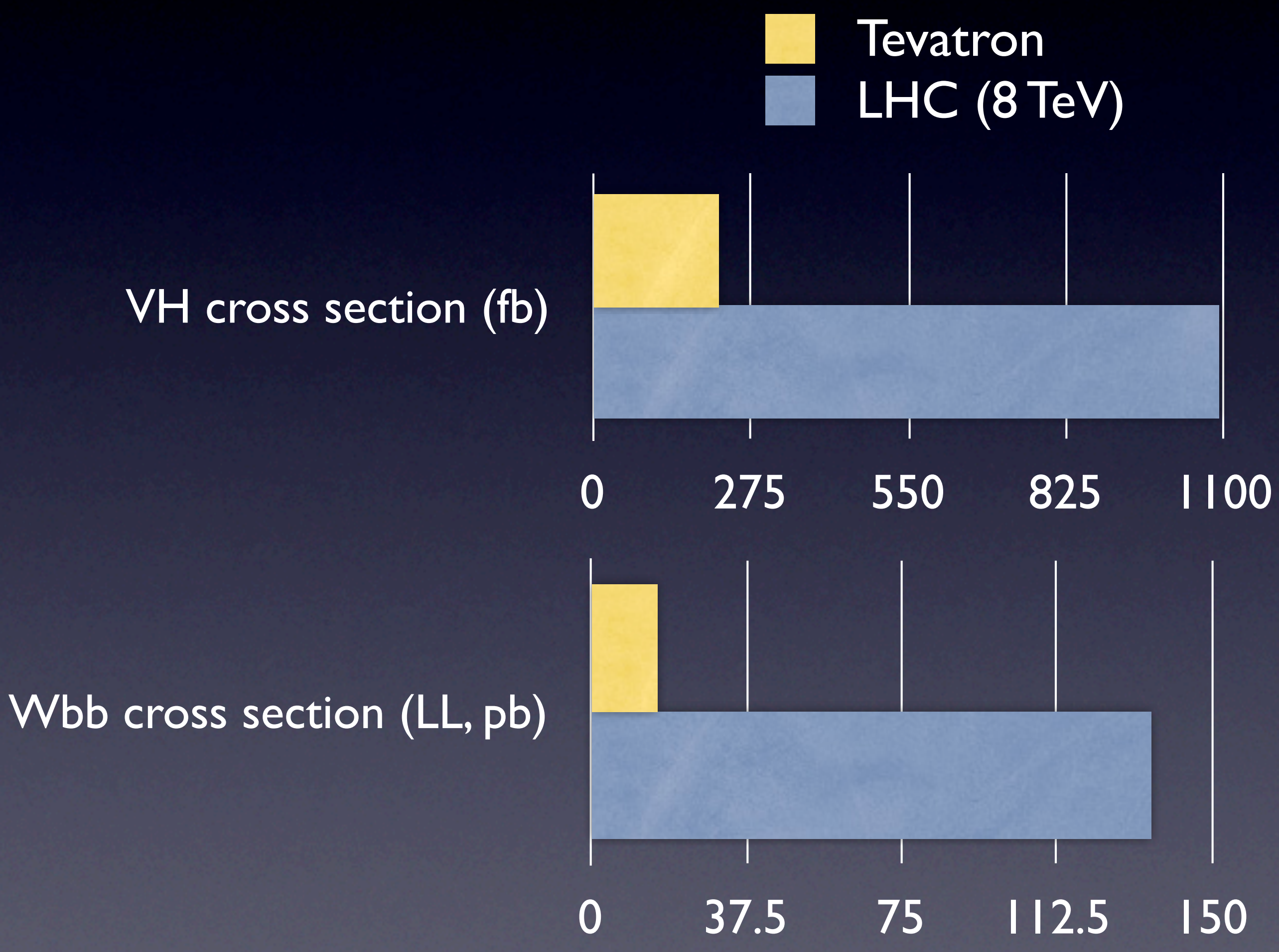
Large SM backgrounds mean that we can only see the Higgs in the VH production mode

Search Strategy

- To maximize sensitivity, searches typically:
  - separate a given final state signature into several subsets with different S/B ratios
    - e.g., based on lepton flavor, number of jets, quality of *b* ID information
  - use multivariate techniques to distinguish signal from background
  - constrain systematic uncertainties with the data

VH at the Tevatron and LHC

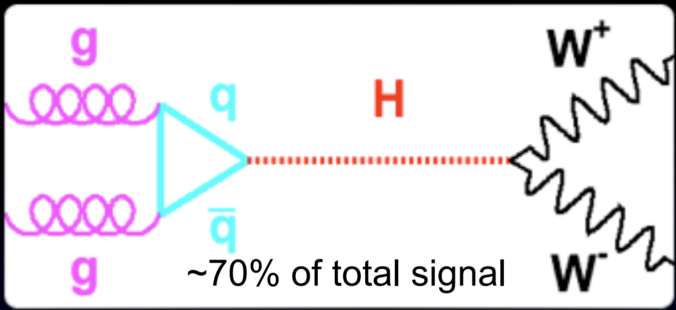
- At a given energy, the *VH* cross section is higher for $p\bar{p}$ than pp
  - but cross section does increase with energy

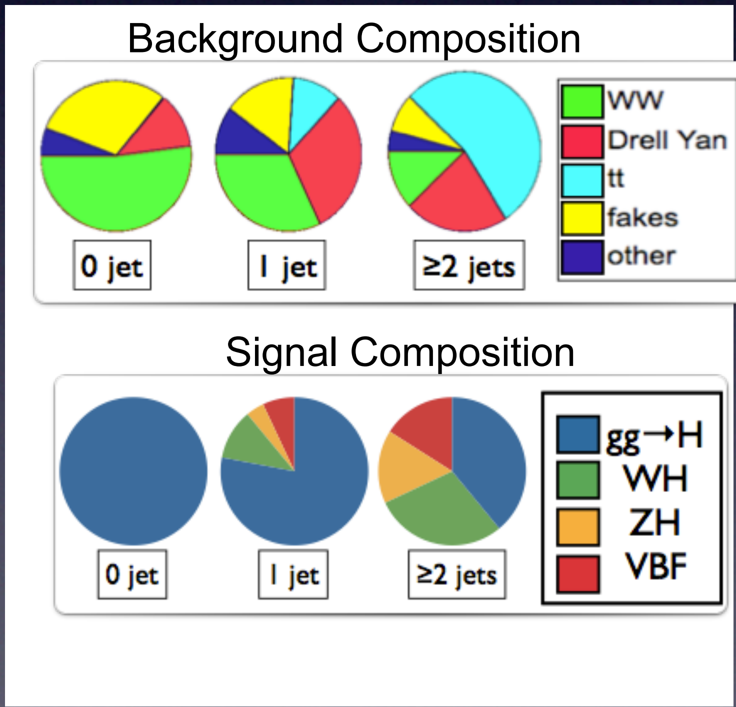


S/B ratio is higher at the Tevatron

Searches at High Mass

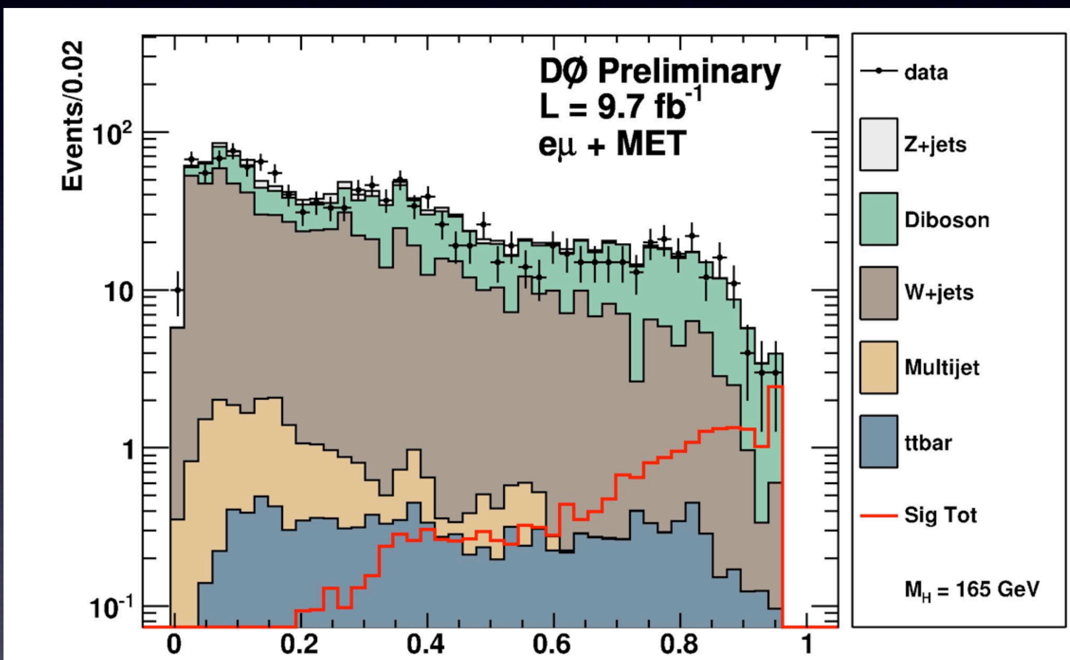
- The best mode for $M_H > \sim 135$ GeV is $gg \rightarrow H \rightarrow WW$
  - we know now that there is no SM Higgs in this mass region
  - these searches are primarily of historical interest
  - used to set first post-LEP Higgs mass exclusion
- To minimize backgrounds, require both W's to decay to $\ell\nu$
  - signal and background composition vary with jet multiplicity



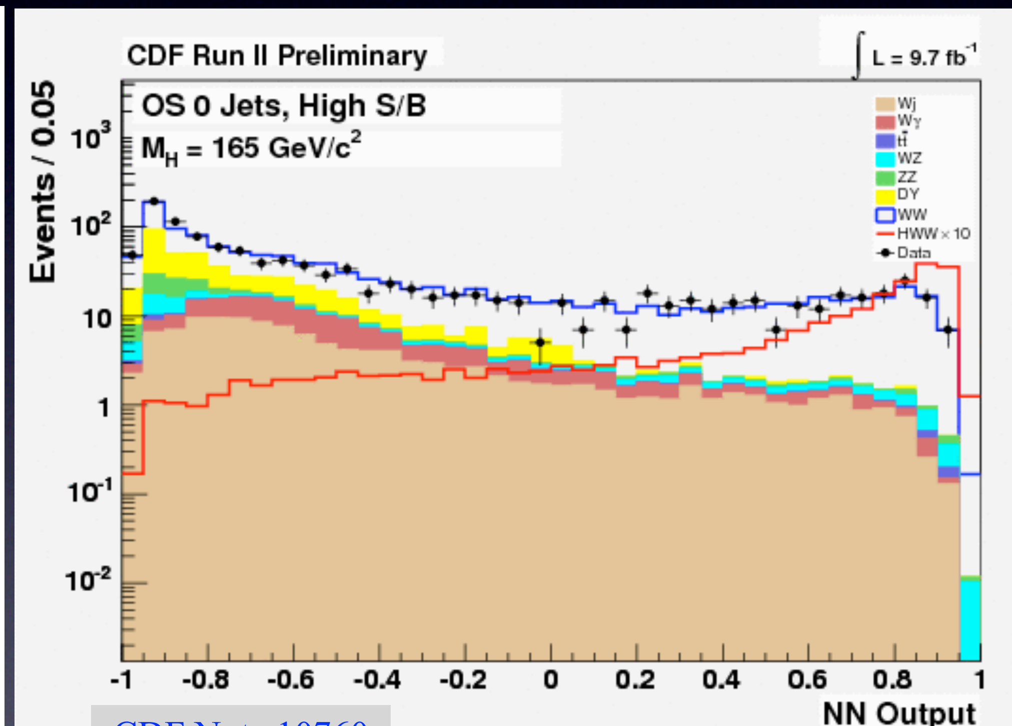


Data Compared to SM Backgrounds

- *eμ*, *ee*, and *μμ* channels are all considered
  - as are all jet multiplicities of 0, 1 or ≥2
- Examples of data distributions:



Phys. Rev. D 86, 032010 (2012)



CDF Note 10760

- No significant excess observed at M_H = 165 GeV

Systematic Uncertainties

- As seen on the previous slide, we are looking for a small signal amidst a large background
  - critical to understand the composition and kinematics of the background in detail
- Systematic uncertainties can affect
  - kinematic (and therefore discriminant) distributions
    - e.g., pdf's, p_T-dependent object ID uncertainties
  - overall normalization
    - e.g., luminosity, theoretical cross sections
- Variations in all systematic uncertainties are considered when fitting data

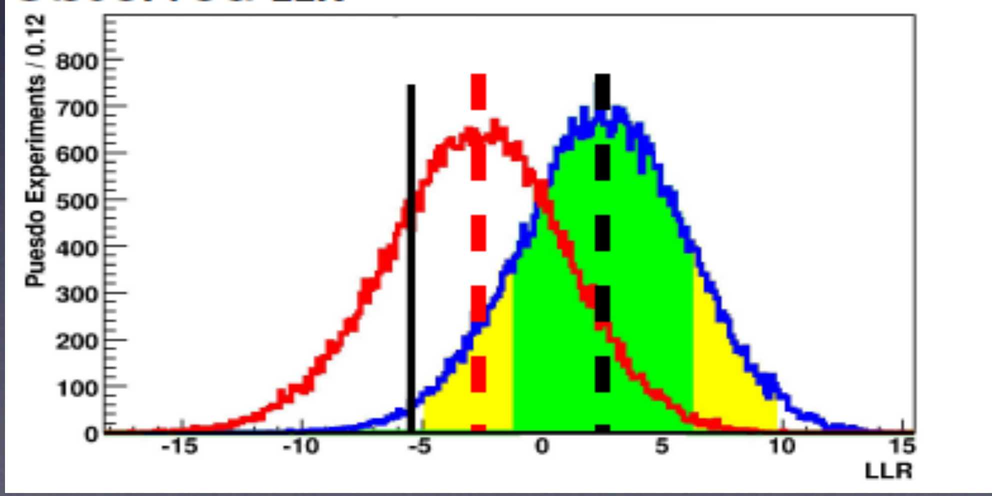
Limit Setting

- Start with the log-likelihood ratio:

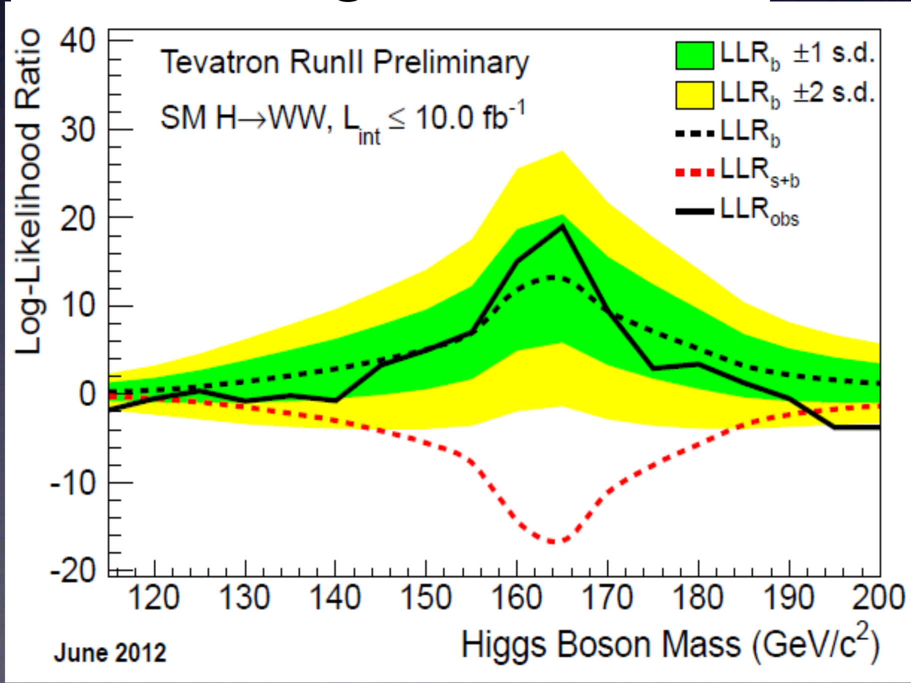
$$\mathrm{LLR} = -2\ln \frac{L\left[S\left(M_H, \sigma_{p\bar{p}\to H+X}\right)+B\right]}{L\left[B\right]}$$

Integrating over systematic uncertainties

At a given M_H and $\sigma_{p\bar{p}\to H+X}$

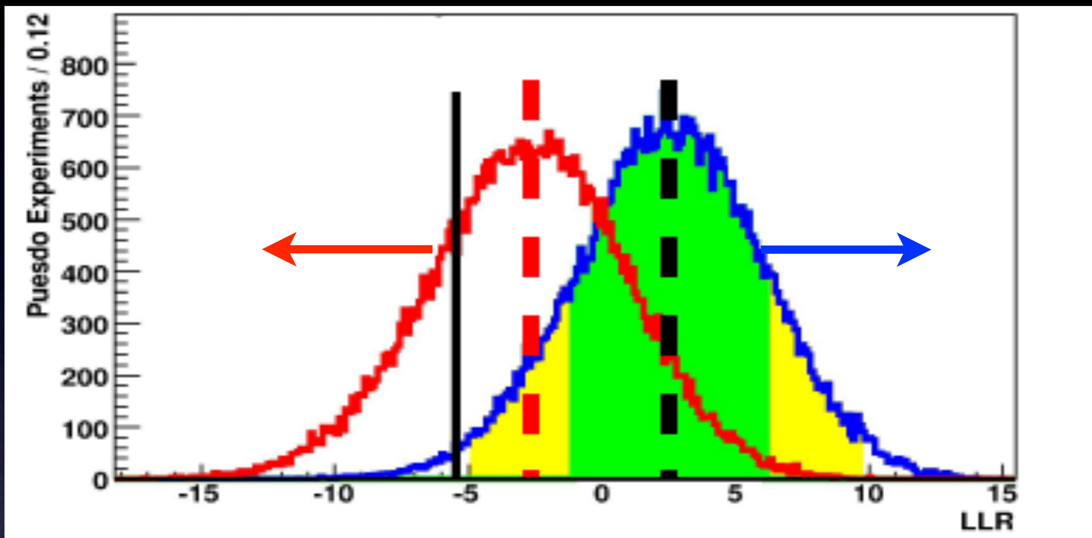


Scanning across M_H



From LLR to Limit

- As we increase the assumed cross section, the expected LLR changes:



We define two quantities:

1. CL_b = fraction of blue curve to the right of the data
2. CL_{s+b} = fraction of red curve to the right of the data

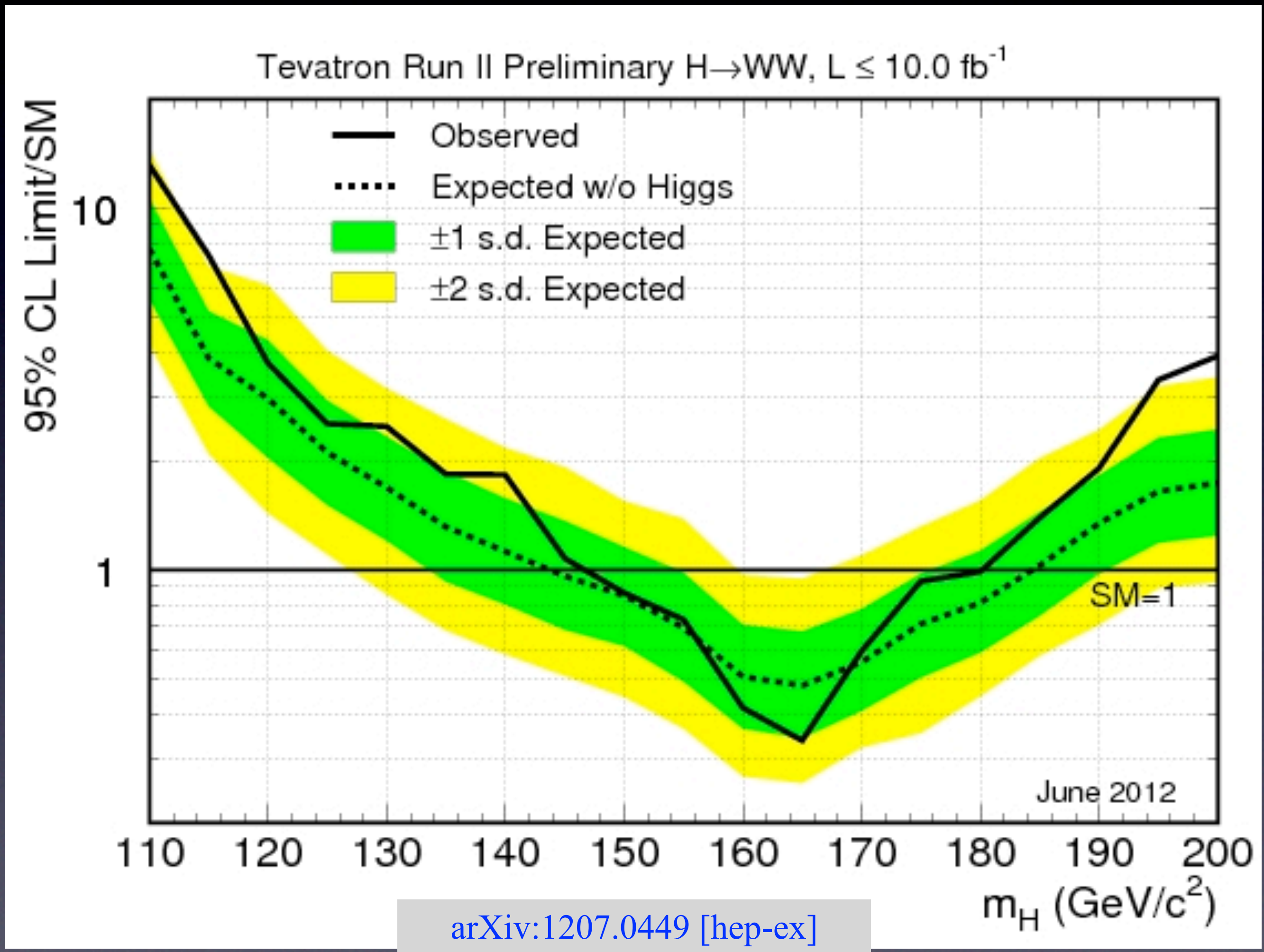
- Then define

$$CL_s = \frac{CL_{s+b}}{CL_s}$$

- If $CL_s < 0.05$, then the assumed cross section is ruled out at 95% C.L.

Tevatron Combined $H \to WW$

- We then plot the limit vs M_H (normalized to the SM cross section)



arXiv:1207.0449 [hep-ex]

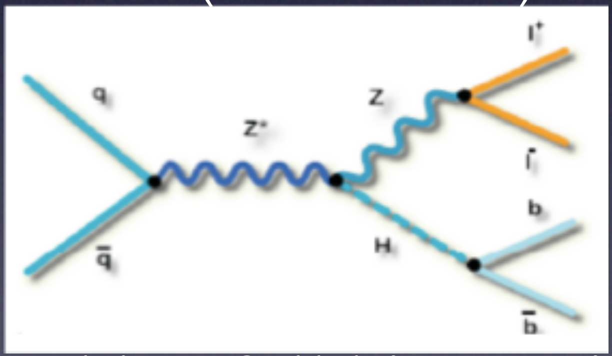
Low Mass Searches

- The most sensitive search channel for $M_H <\sim 130$ GeV is

$$q\bar{q} \rightarrow (W,Z)H \rightarrow \ell\ell' b\bar{b}$$

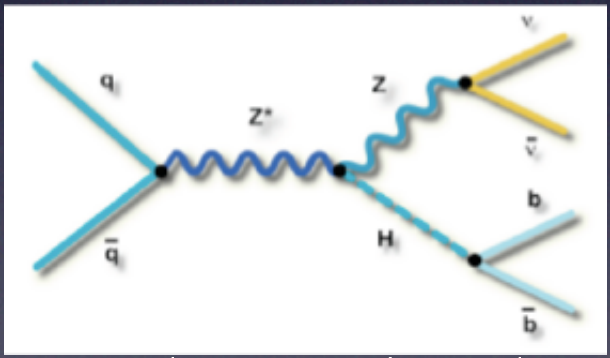
- Here we have a complementarity with the LHC
  - we are most sensitive to a fermionic decay
  - the LHC observation rests solely on decays to bosons
- Search done in the channels:

$ZH \rightarrow (e^+e^-, \mu^+\mu^-)b\bar{b}$



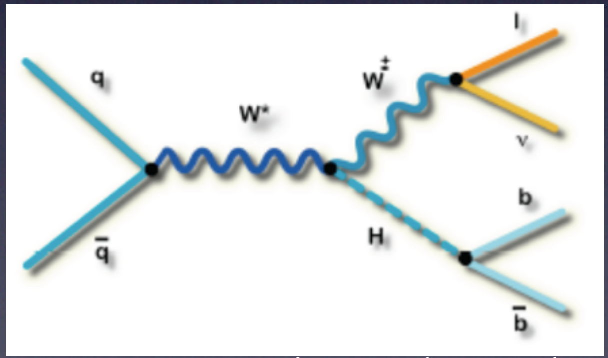
Low bkg, full kinematics
Small $\sigma\times$BR

$ZH \rightarrow \nu\nu b\bar{b}$



$3\times$ larger signal
Challenging bkg.

$WH \rightarrow (e,\mu)\nu b\bar{b}$

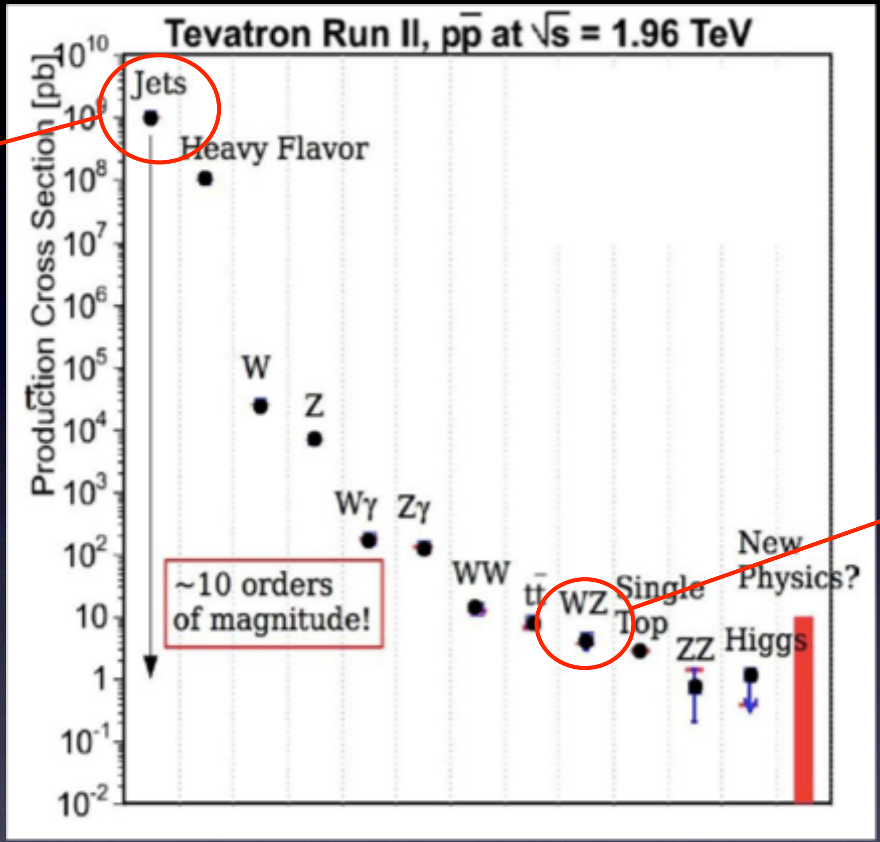


Larger signal and
bkg. than $ZH \rightarrow \ell\ell bb$

Backgrounds

- Backgrounds to the low mass search can have

Large cross sections, small chance of mimicking final state

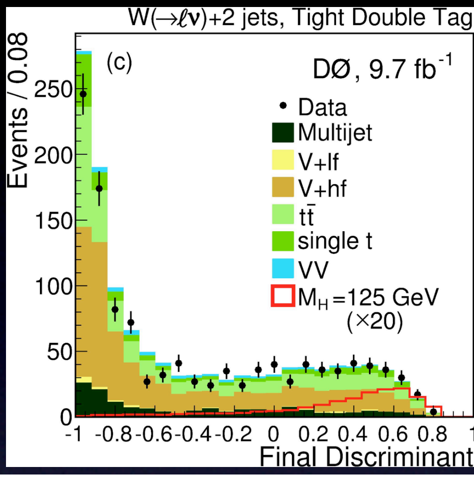


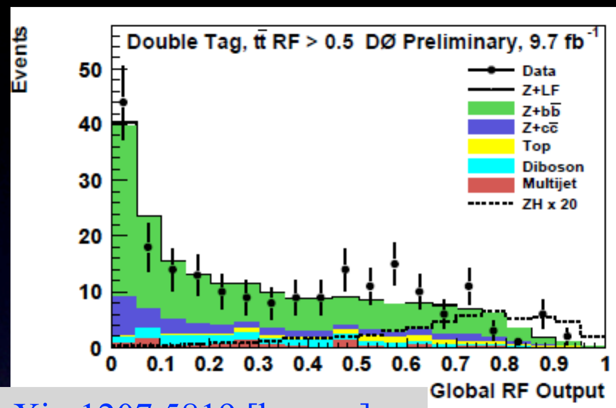
Small cross sections, same final state

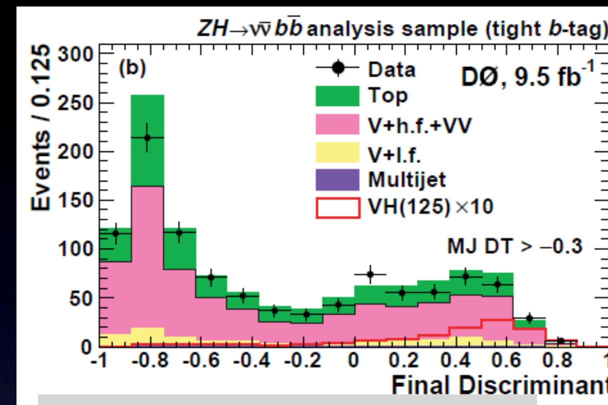
- Data control samples supplement MC predictions to model rate and distributions of all backgrounds

DØ Results

$WH \rightarrow \ell \nu b\bar{b}$	$ZH \rightarrow \ell\ell b\bar{b}$	$ZH \rightarrow \nu\nu b\bar{b}$

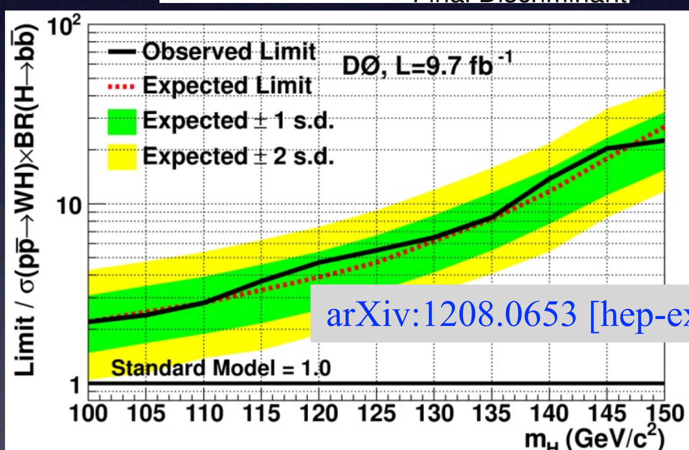




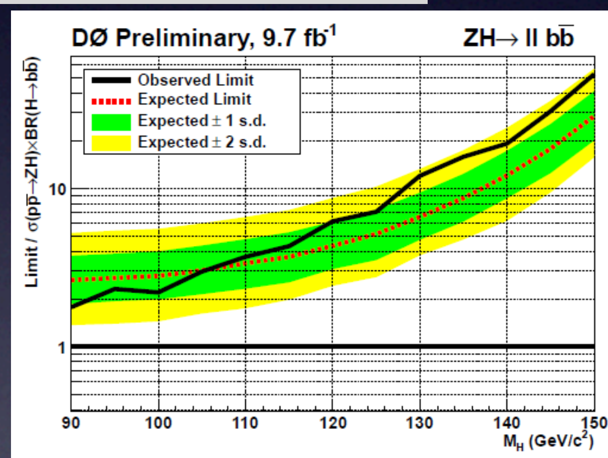


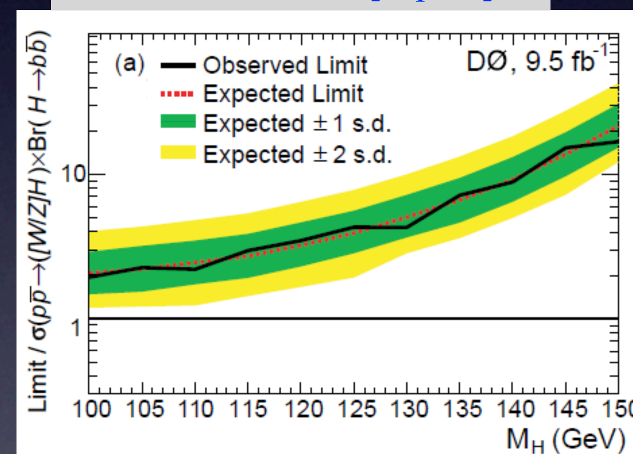
arXiv:1207.5819 [hep-ex]

arXiv:1207.5689 [hep-ex]



arXiv:1208.0653 [hep-ex]

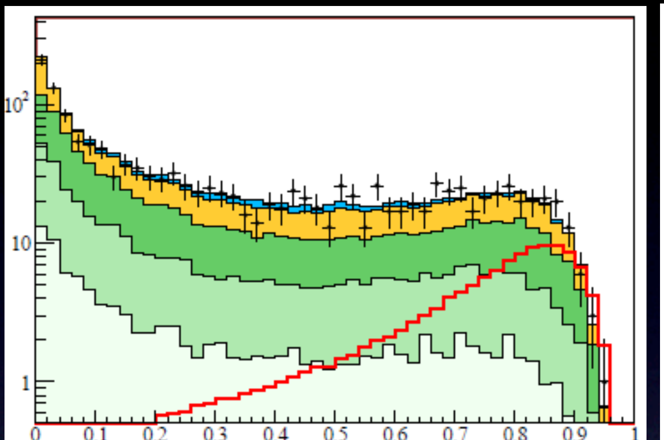


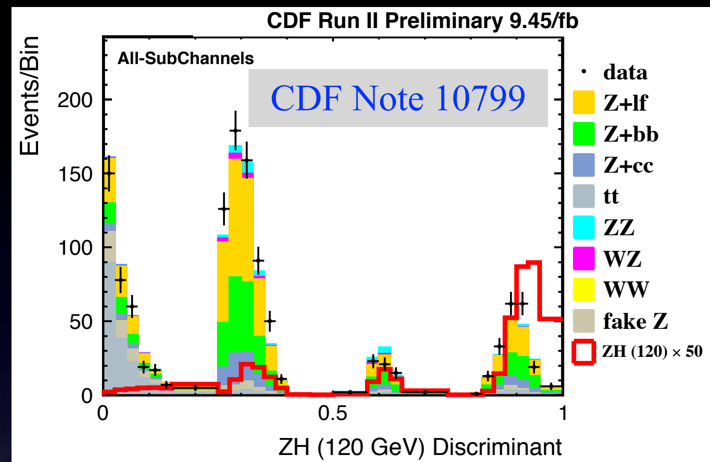


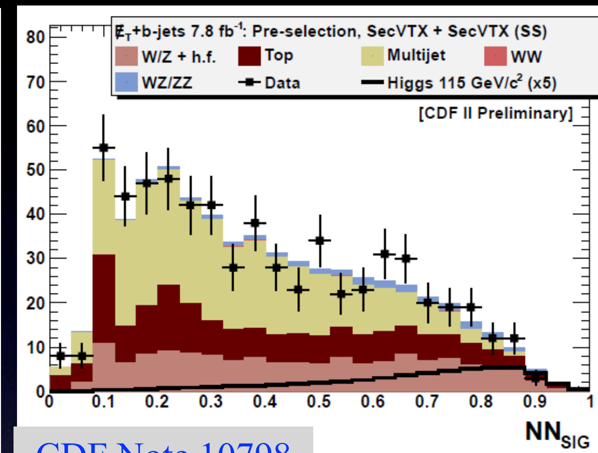
- No significant excess seen
  - but single channels are not sensitive to SM Higgs

CDF Results

$WH \rightarrow \ell \nu b\bar{b}$ | $ZH \rightarrow \ell\ell b\bar{b}$ | $ZH \rightarrow \nu\nu b\bar{b}$

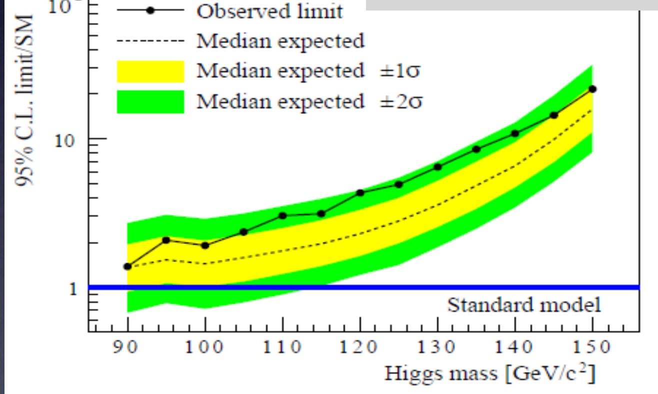


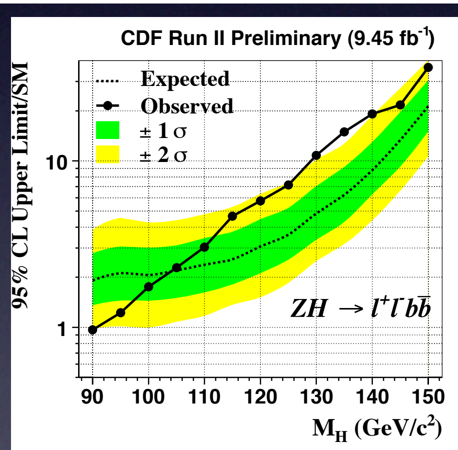


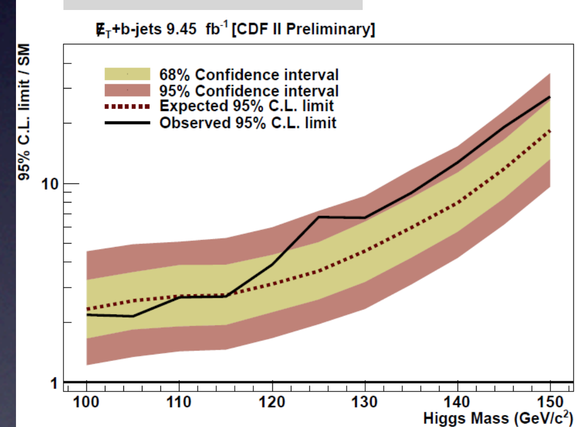


CDF Note 10798

CDF Note 10796







- Some larger excesses seen here
  - not enough to make any clear statement

Diboson Cross Check

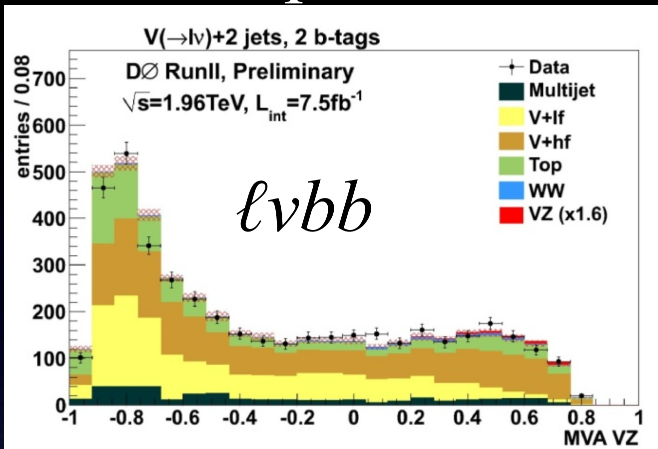
- The analyses are necessarily complex
- To validate the procedure, we treat *WZ*/*ZZ* production as the signal we're looking for
  - i.e. replacing $H \rightarrow bb$ with $Z \rightarrow bb$ (keeping *WW* as bkg.)
- Comparing cross sections (M_H = 125 GeV):

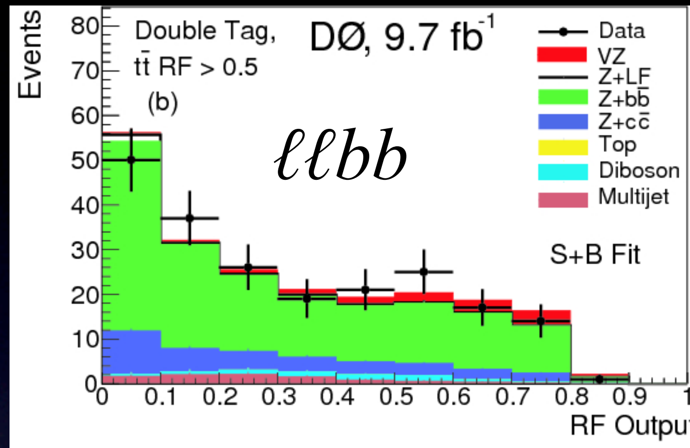
Final state	σ×BR with $H \rightarrow bb$	σ×BR with $Z \rightarrow bb$
$\ell \nu bb$	16 fb	105 fb
$\nu\nu bb$	9 fb	81 fb
$\ell\ell bb$	3 fb	27 fb
Total	28 fb	213 fb

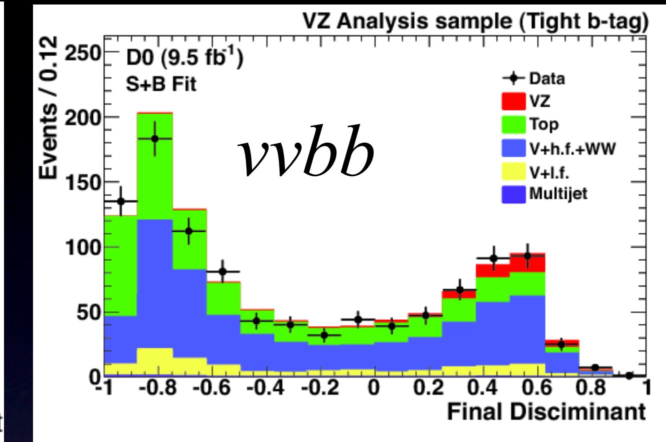
- Lower mass of *Z* makes *W*+jets, multijet, and *WW* backgrounds more challenging

Diboson Results

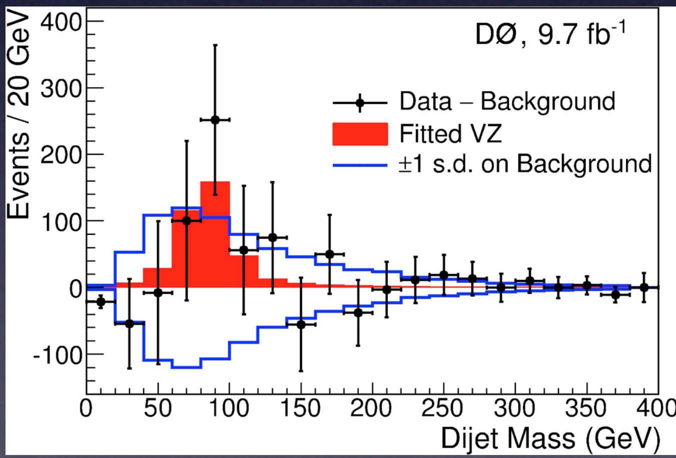
- Examples of final discriminant distributions:

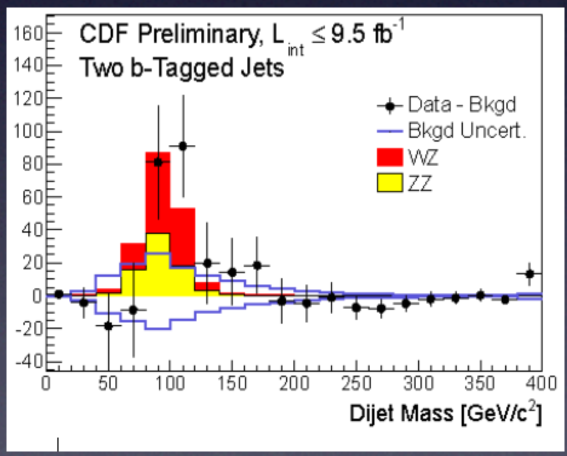






- and dijet mass distributions (3 channels combined)

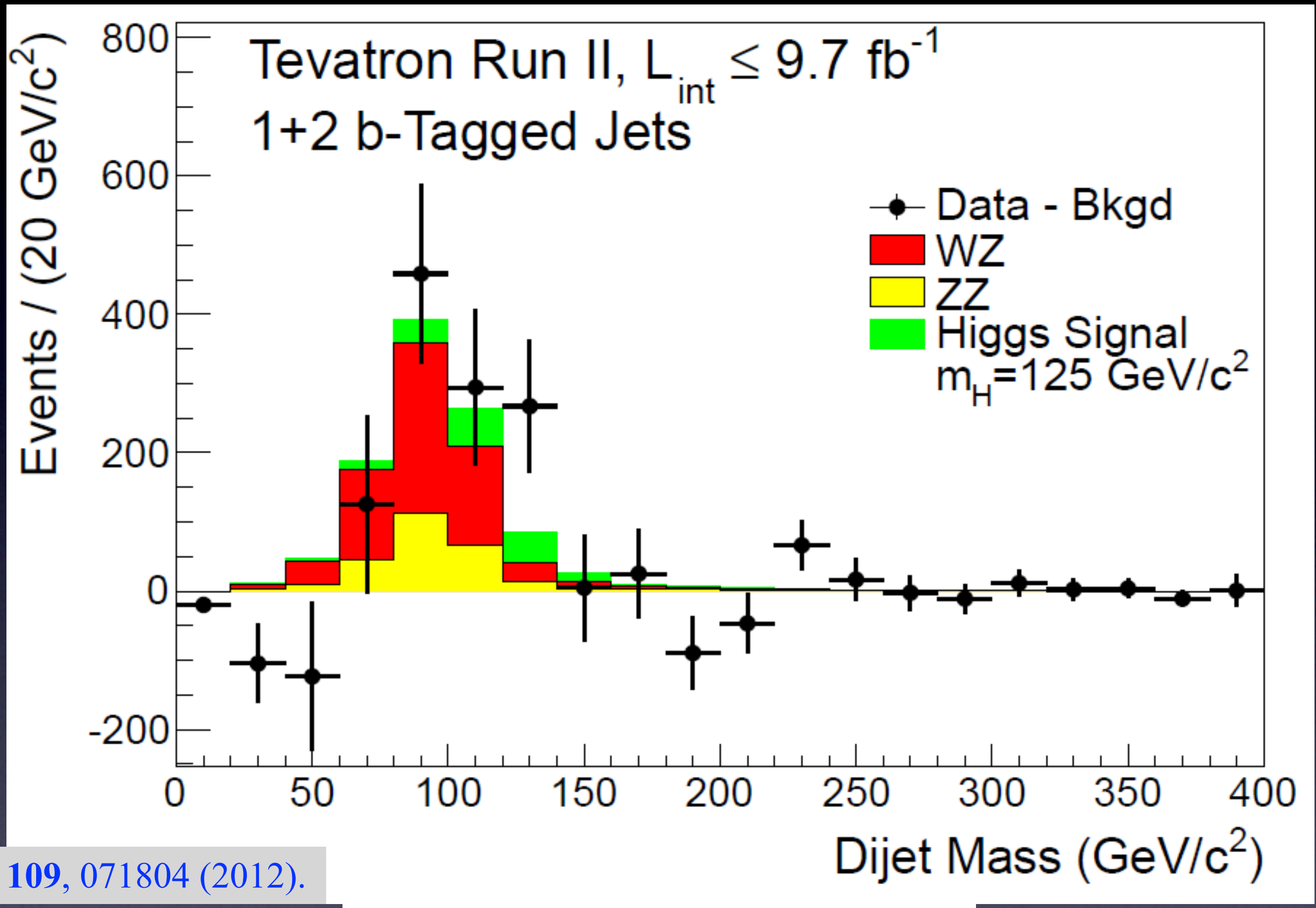




- >3σ evidence/experiment, with cross section consistent with SM

Diboson Combination

- Combining the diboson results from both experiments:



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

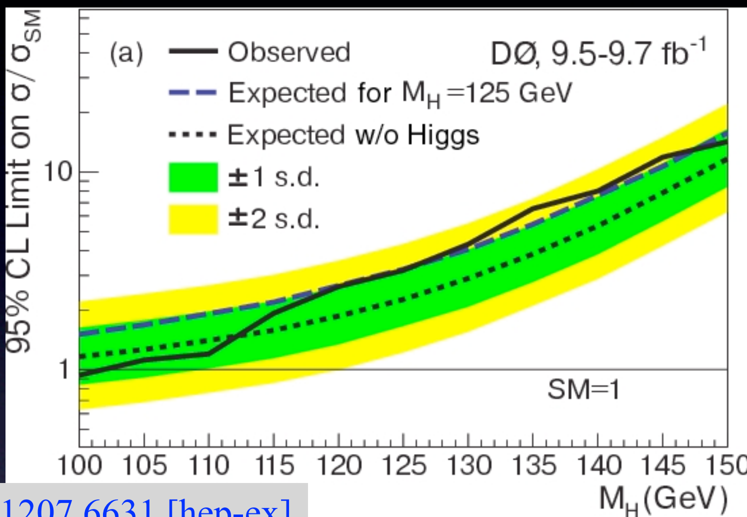
Significance > 4.5σ

$\sigma_{WZ/ZZ} = 3.9 \pm 0.9$ pb

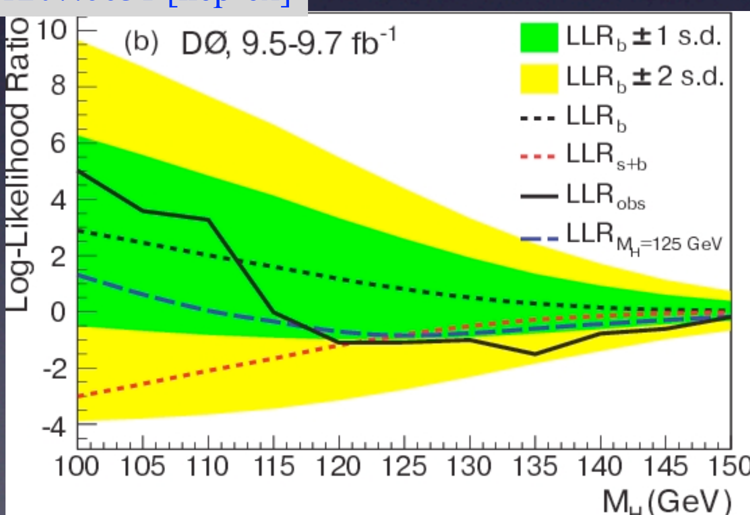
$\sigma_{SM} = 4.4 \pm 0.3$ pb

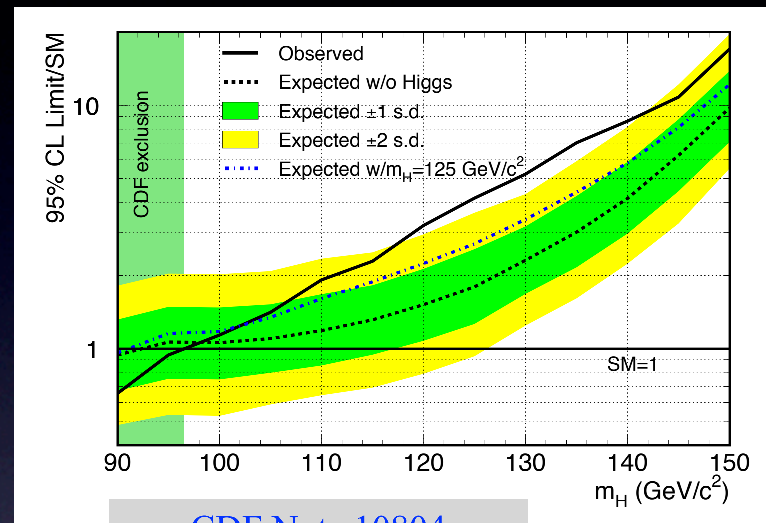
Combining $H \to bb$ Searches

- When the three $H \to bb$ channels are combined within each experiment, something interesting begins to emerge:



arXiv:1207.6631 [hep-ex]





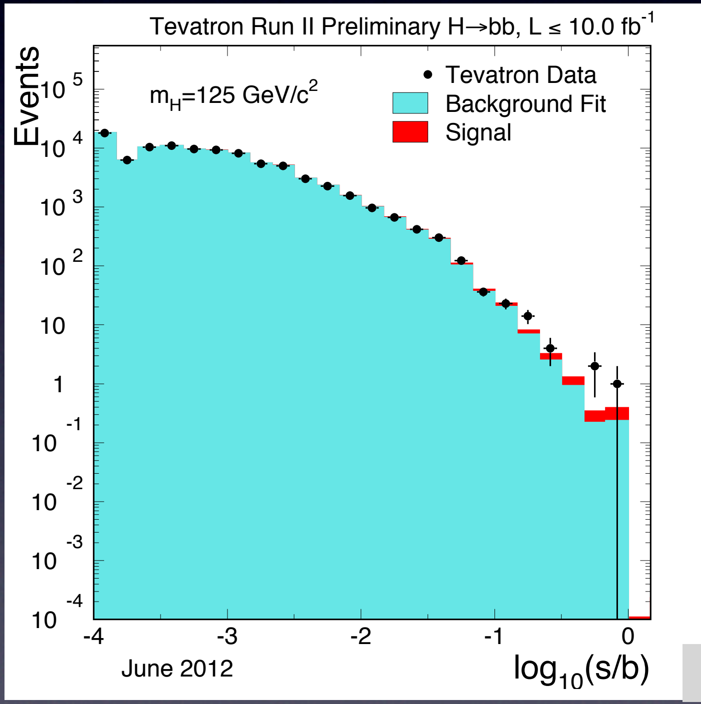
CDF Note 10804

- Both CDF and DØ see an excess over background for $\sim 120 < M_H < 145$ GeV
- Significance: 2.5σ for CDF, 1.5σ for DØ

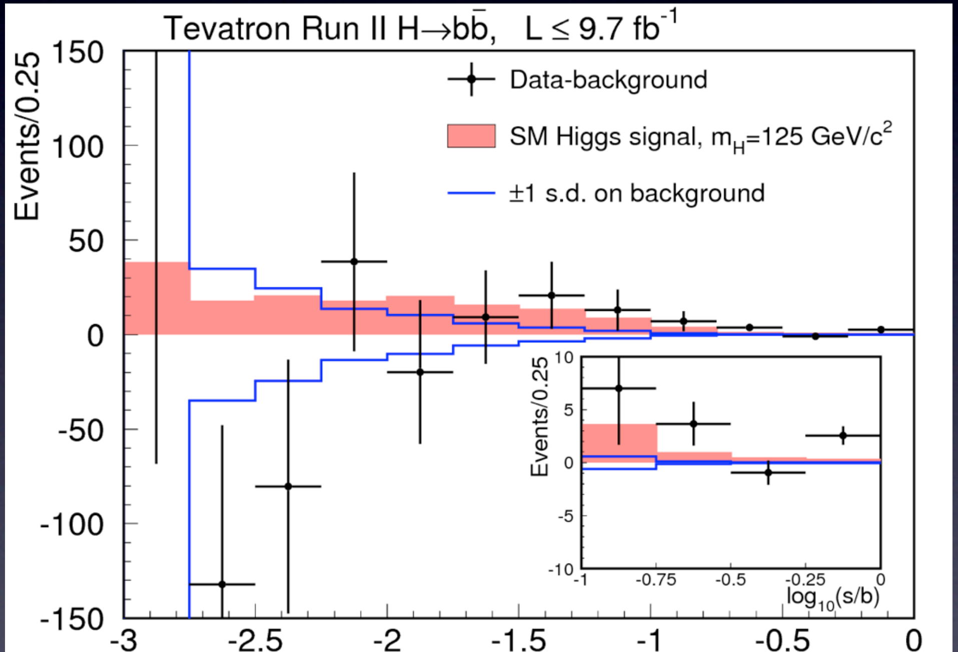
Tevatron *H→bb* Combination

- Combined data sample
- Binned in increasing S/B ratio, based on final discriminant value:

All data



Background-subtracted

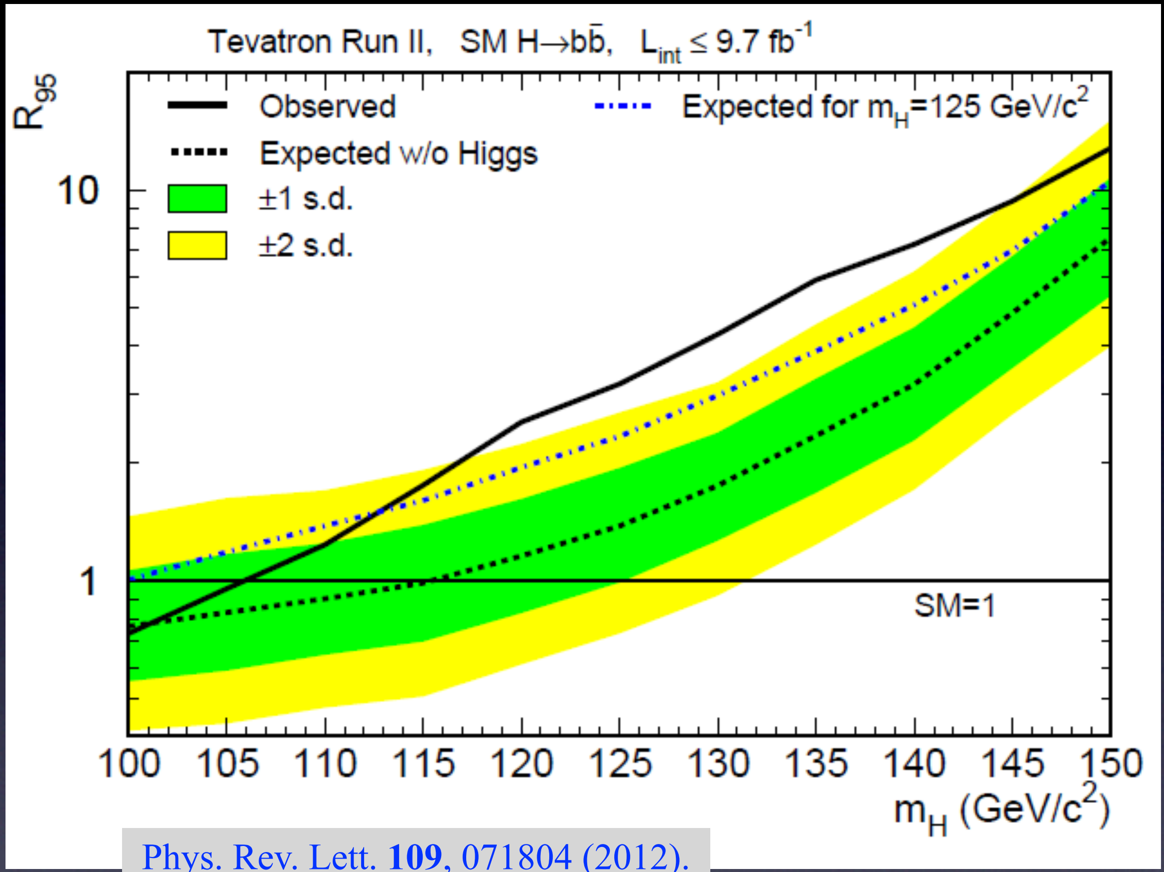


Phys. Rev. Lett. **109**, 071804 (2012).

Excess of events in the high S/B region

Tevatron $H \rightarrow bb$ Combination

- Combined cross section limits:

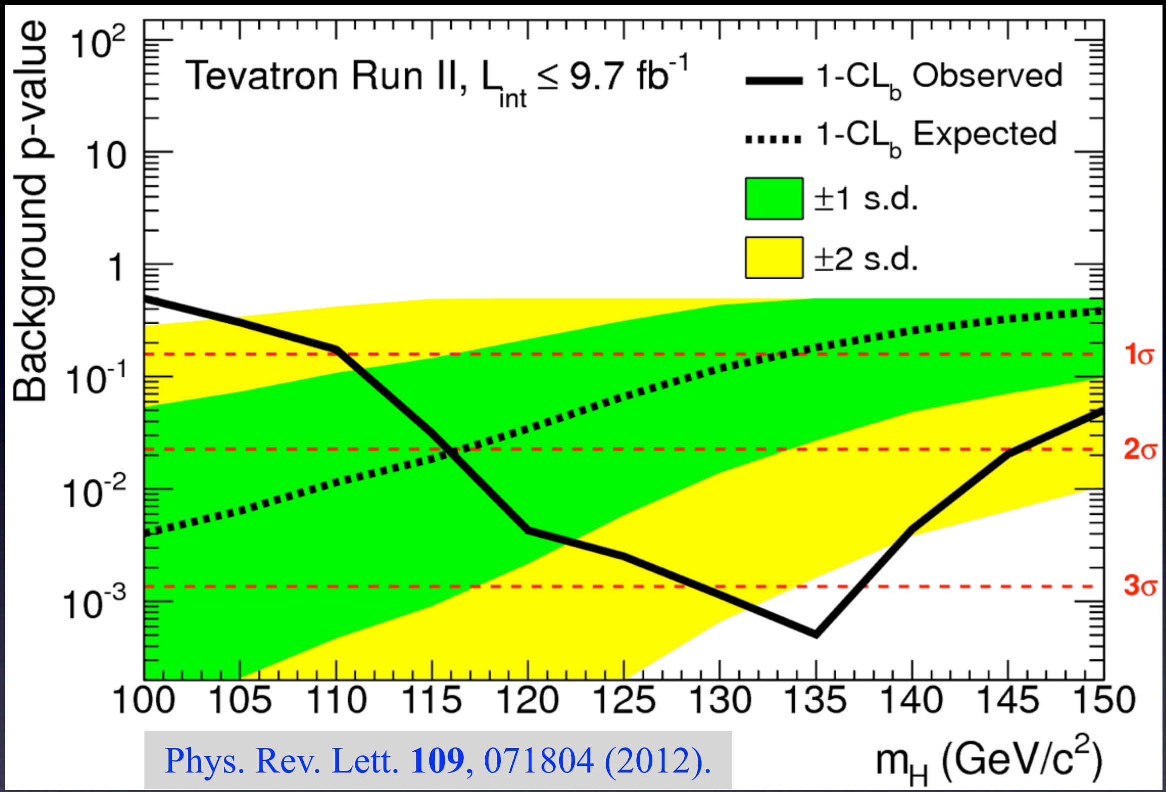


Phys. Rev. Lett. **109**, 071804 (2012).

- The excess in data results in a less stringent limit than expected
  - effect is strongest for $\sim 120 < M_H < 135$ GeV

Significance of Excess

- *p*-value for background producing the observed excess:

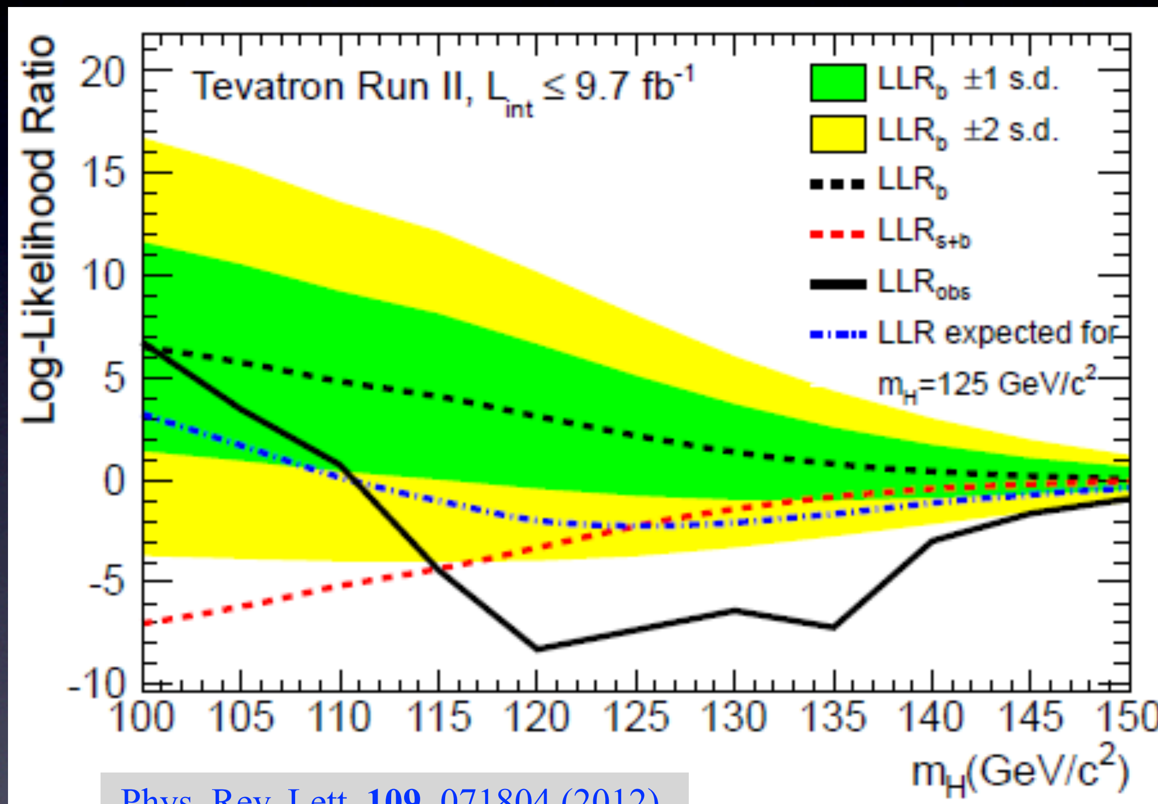


Phys. Rev. Lett. **109**, 071804 (2012).

- Largest local significance is 3.3σ at 135 GeV
  - becomes 3.1σ when accounting for look-elsewhere effect
- Local significance at 125 GeV is 2.8σ

Signal Injection

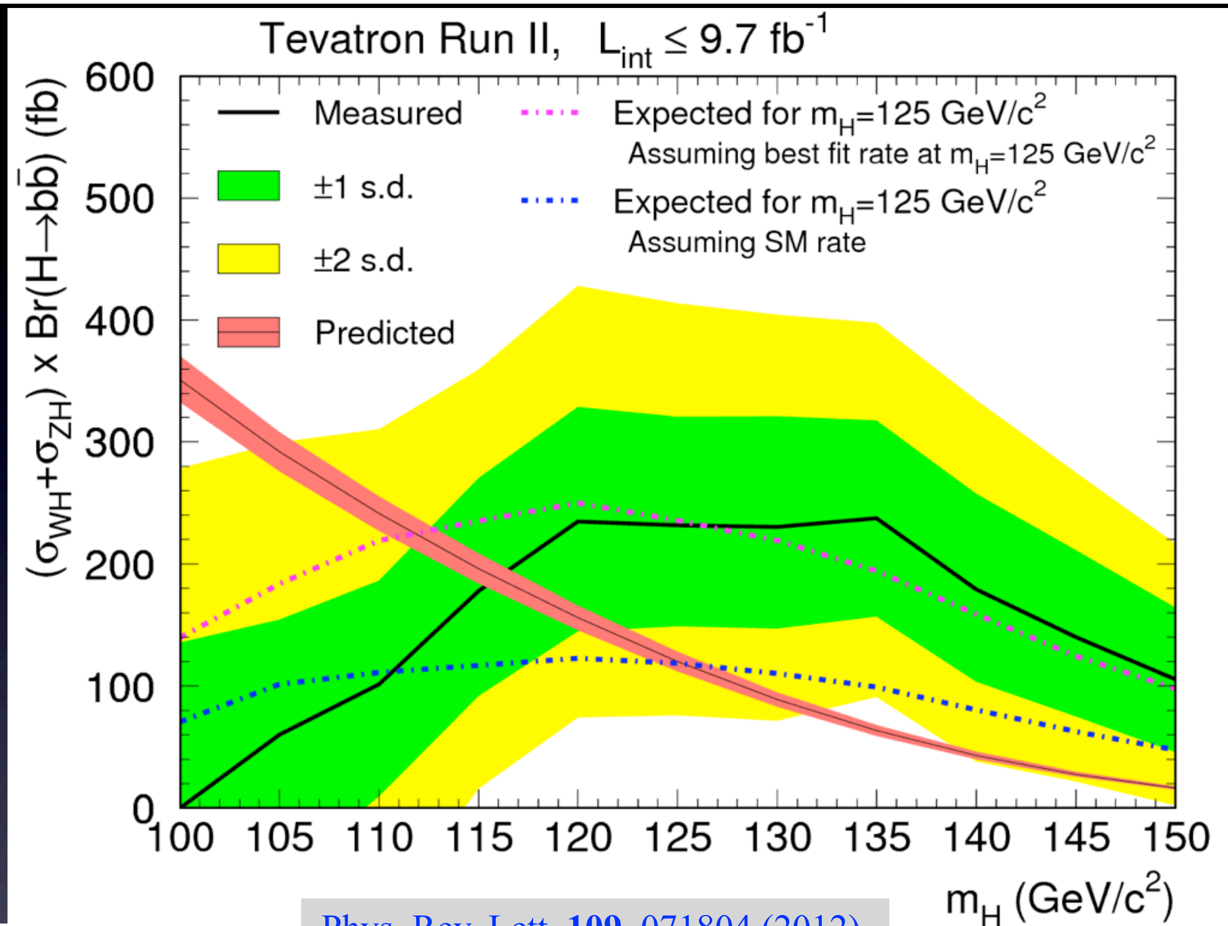
- Add SM Higgs (M_H = 125 GeV) to MC pseudo-experiments
  - allows us to compare observed excess to SM expectation



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

- Observed dependence on mass is consistent

Measured σ×BR



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

For $M_H = 125$ GeV:

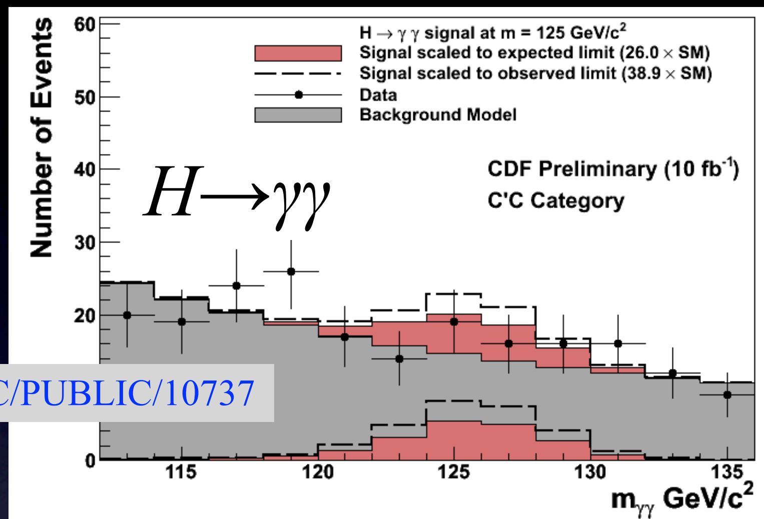
$$\sigma_{p\bar{p}\rightarrow(W,Z)H} \times BR\left(H \rightarrow b\bar{b}\right) = 0.23^{+0.09}_{-0.08}\left(\text{stat.+syst.}\right)\ \text{pb}$$

$$\text{SM prediction} = 0.12 \pm 0.01\ \text{pb}$$

Other Search Channels

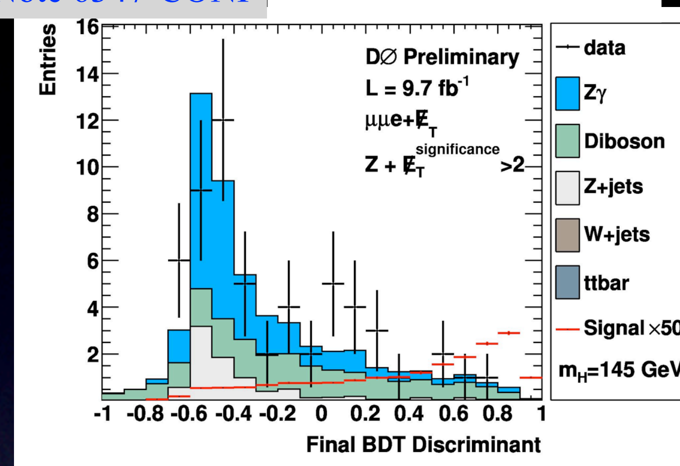
- Examples:

CDF/PUB/EXOTIC/PUBLIC/10737



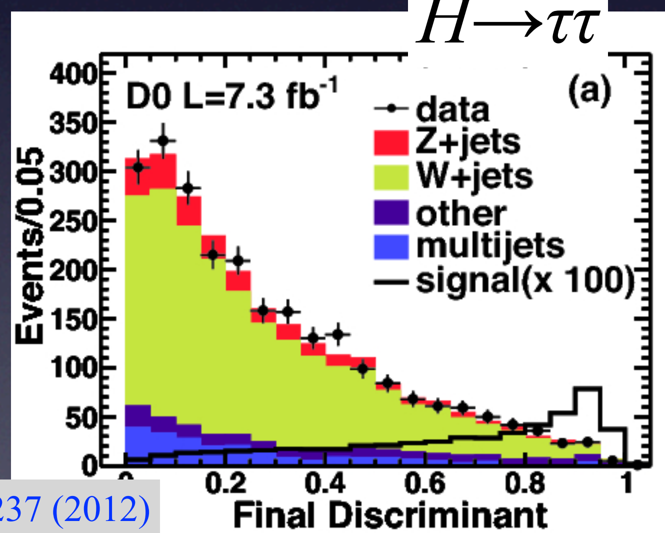
D0 Note 6347-CONF

WH→WWW



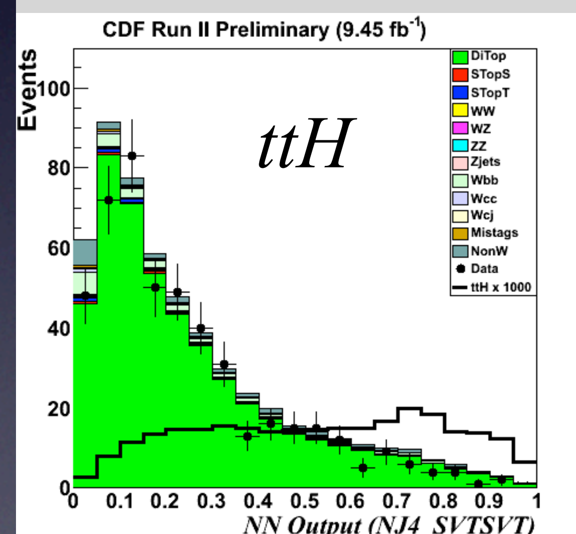
- None of these are individually sensitive to SM Higgs

H→ττ



Phys. Lett. B **714**, 237 (2012)

CDF/PUB/EXOTIC/PUBLIC/10801

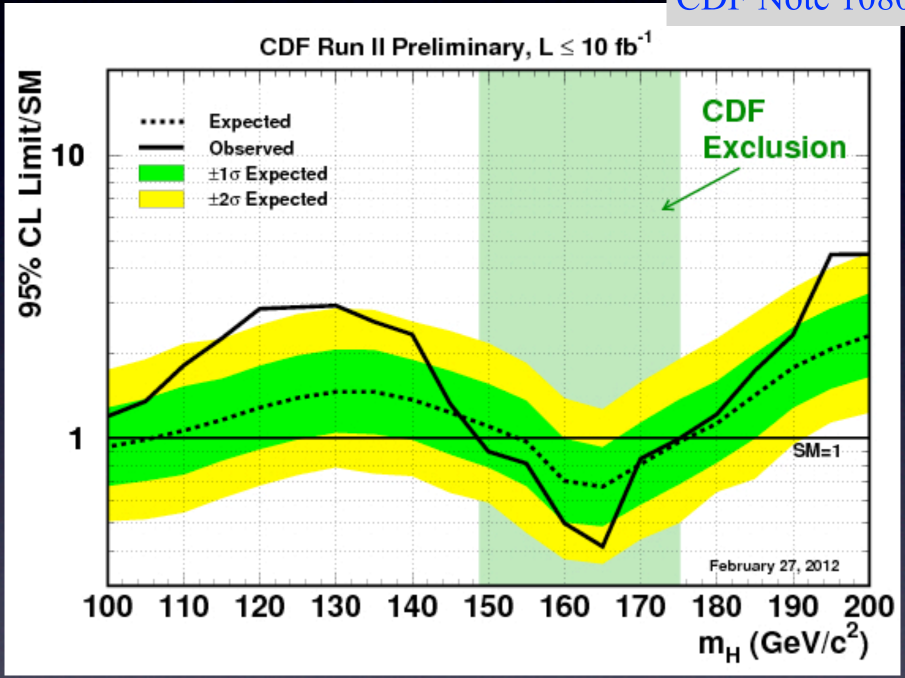


- But they add ~10% to the Tevatron's overall sensitivity

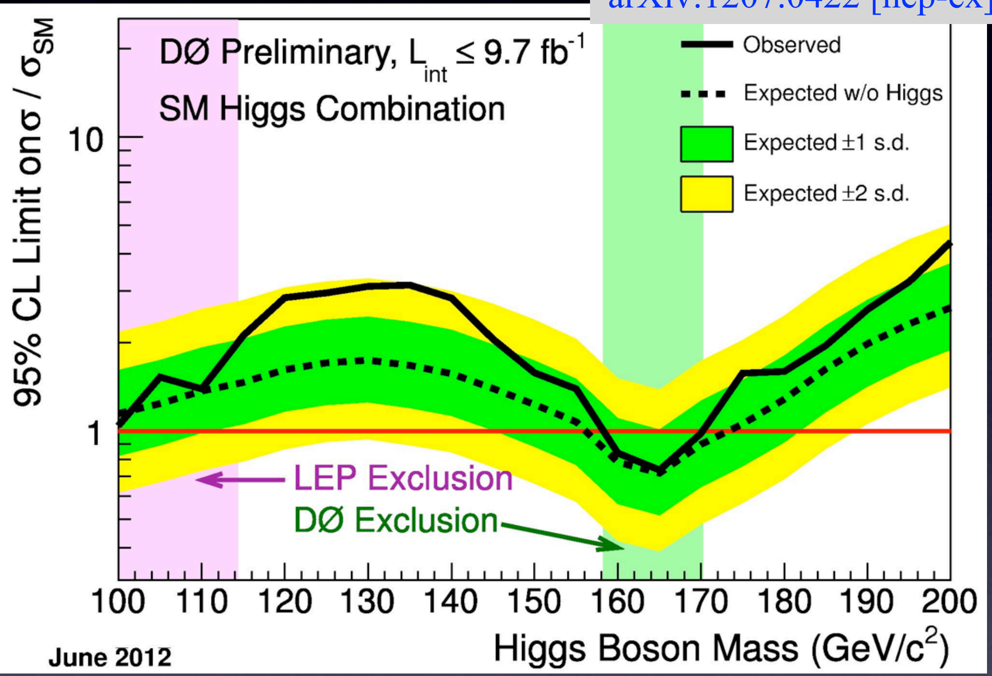
Combining All Channels

- As a first step, all channels are combined within each experiment
- Resulting limits:

CDF Note 10804



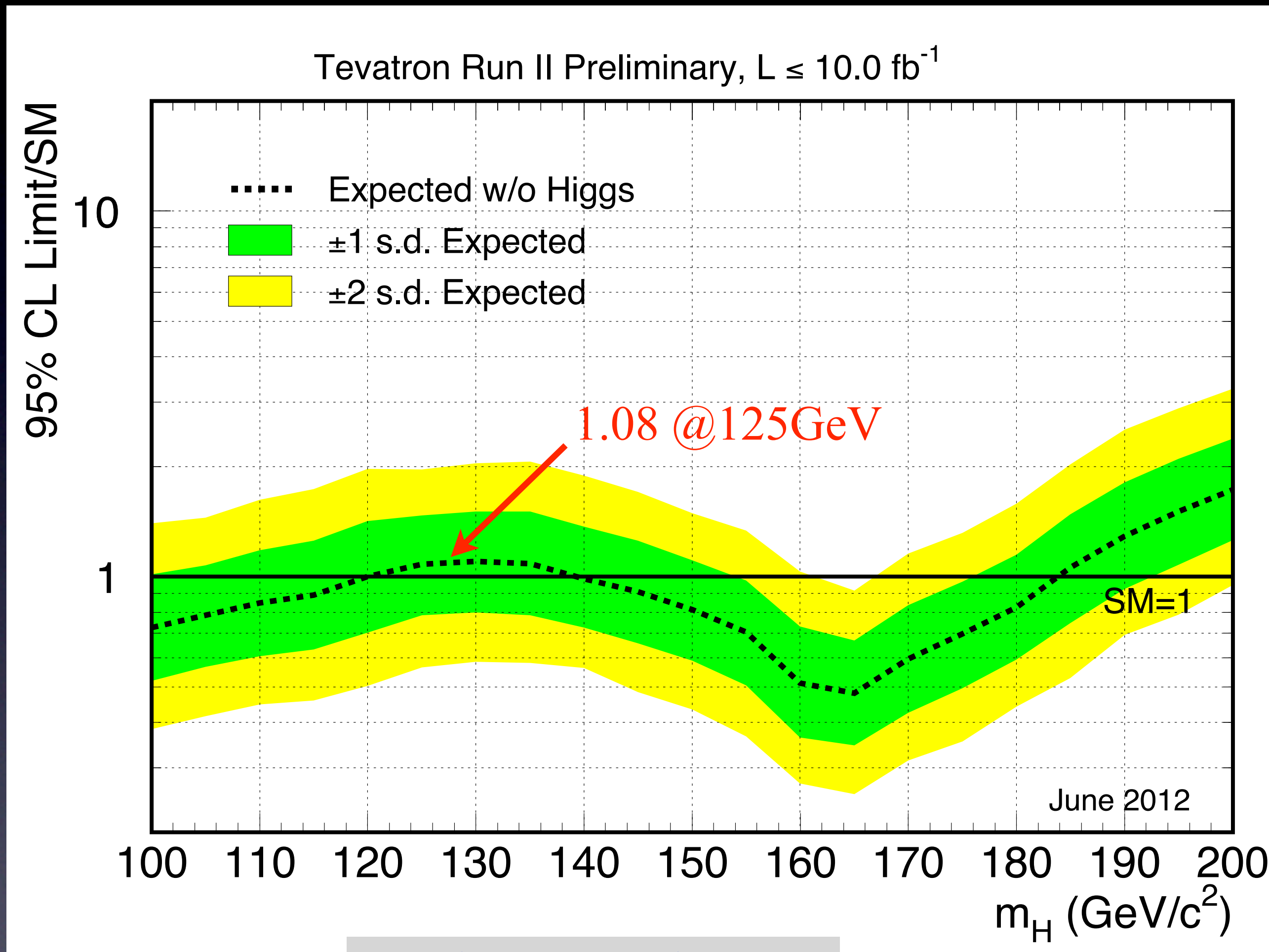
arXiv:1207.0422 [hep-ex]



- Each experiment is sensitive to a broad range of Higgs masses
  - observed limits at low masses not as strong as expected

Tevatron Combination (Expected)

- First calculate expected limits in the absence of Higgs signal

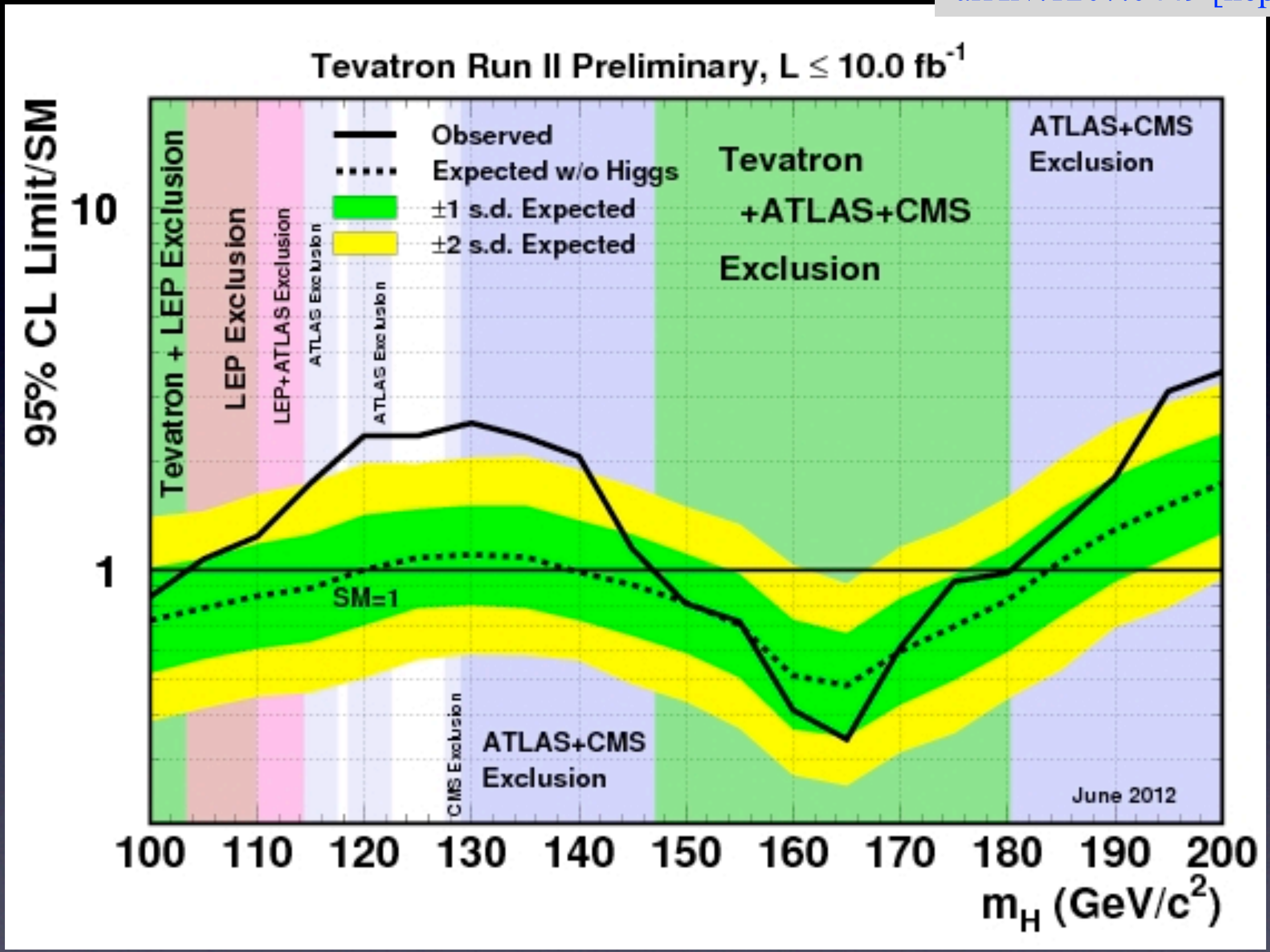


arXiv:1207.0449 [hep-ex]

Tevatron Combination (Observed)

- Looking at the data, we find:

arXiv:1207.0449 [hep-ex]

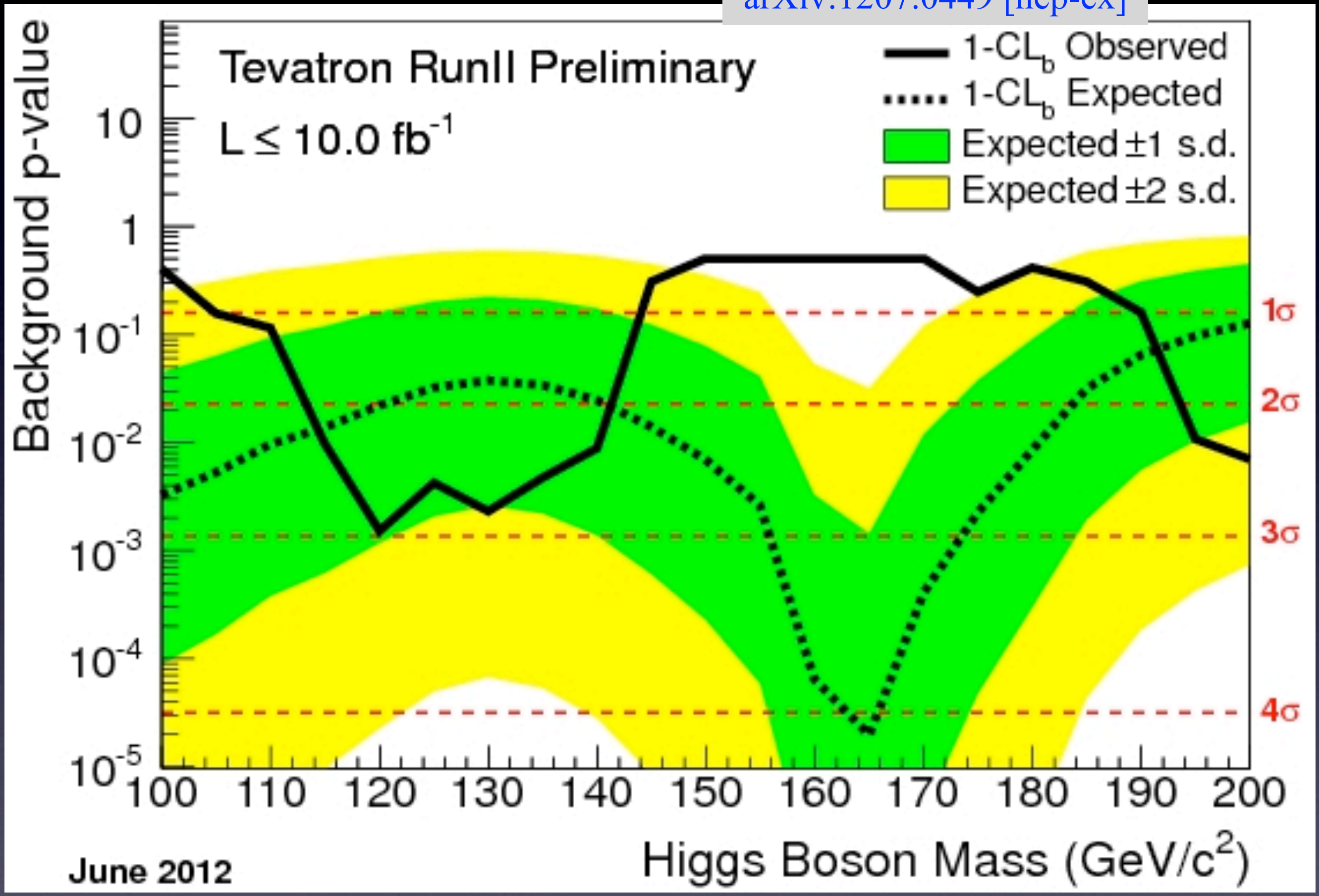


- Exclude $M_H < 103$ GeV, $147 < M_H < 180$ GeV
  - excess seen from ~115 to 140 GeV

Significance

- Probability for background-only data sample to yield excess larger than observed:

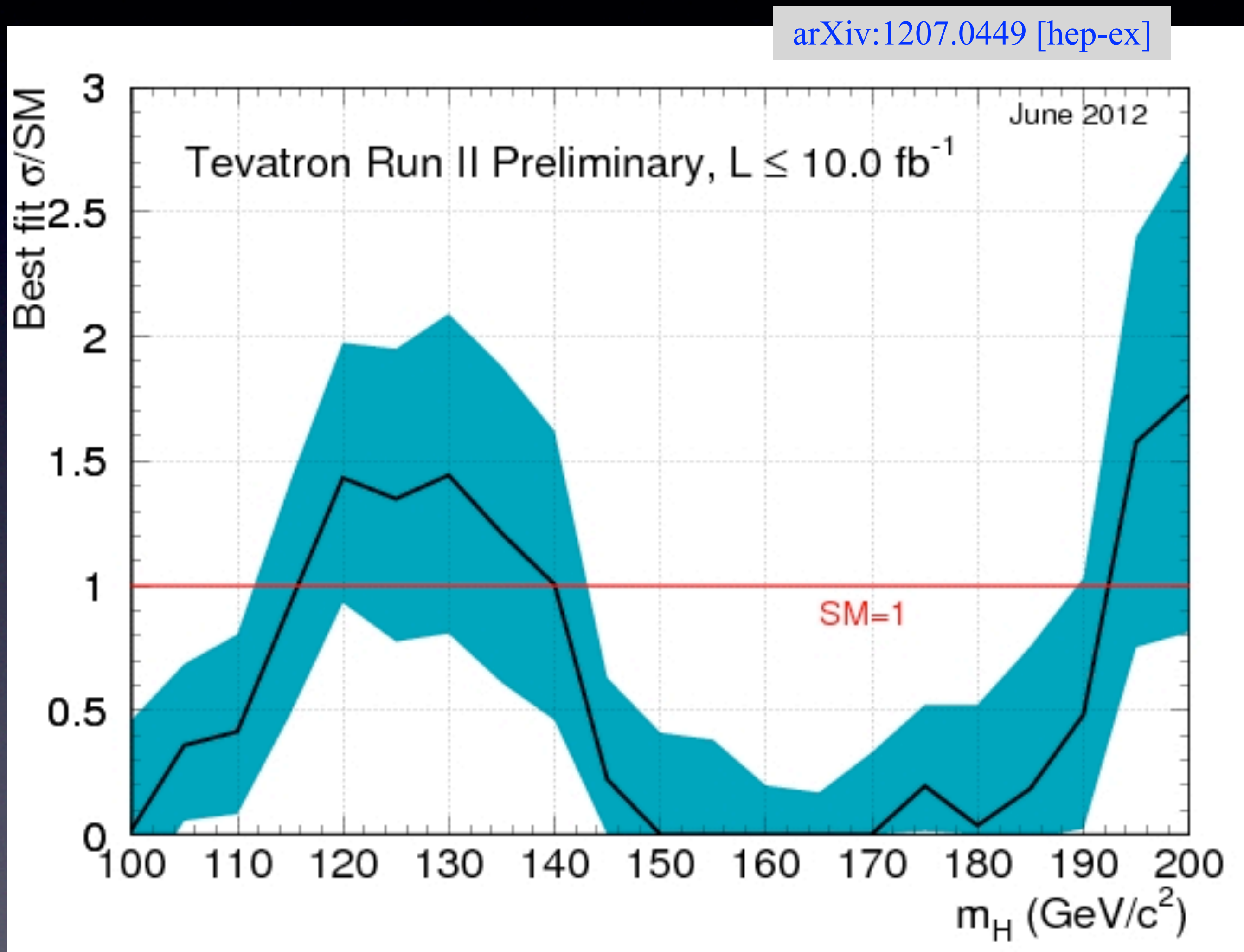
arXiv:1207.0449 [hep-ex]



- Translates to 3.0σ excess at 120 GeV
  - 2.5σ including look-elsewhere effect

Measured Cross Section

- Compare best-fit Higgs production cross section to SM expectation for each M_H hypothesis:

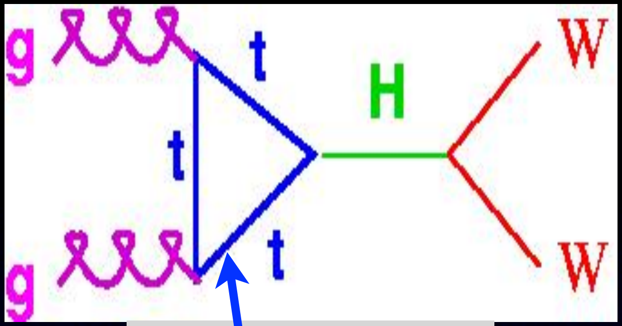


Searches for BSM Higgs

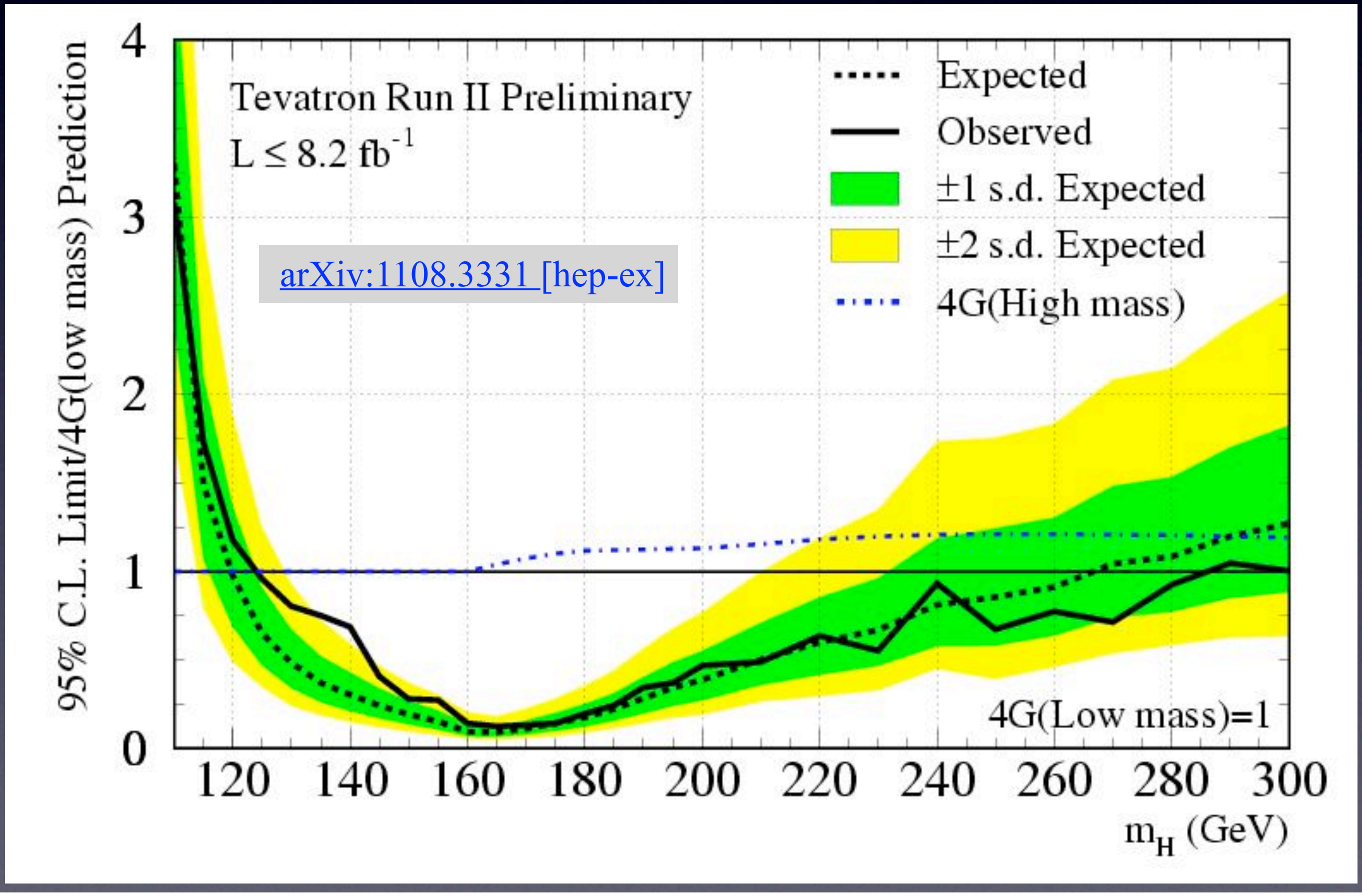
- Higgs boson couplings can be altered in extensions to the SM
- Examples:
  - models with a 4th fermion generation
  - fermiophobic models (generic class of models where the Higgs boson does not couple to fermions)
    - ✦ note that these are now disfavored by the $H \rightarrow bb$ evidence
  - SUSY (couplings are dependent on model parameters, particularly $\tan\beta$)
    - ✦ Tevatron has S/B advantage in *bb* decay modes
  - Hidden Valley models can produce couplings to new particles

4th Generation Models

- 4th fermion generation would increase $gg \to H$ cross section by ~x9
  - and alter decay BR's
- Re-interpretation of Higgs search gives:



Two more quark loops

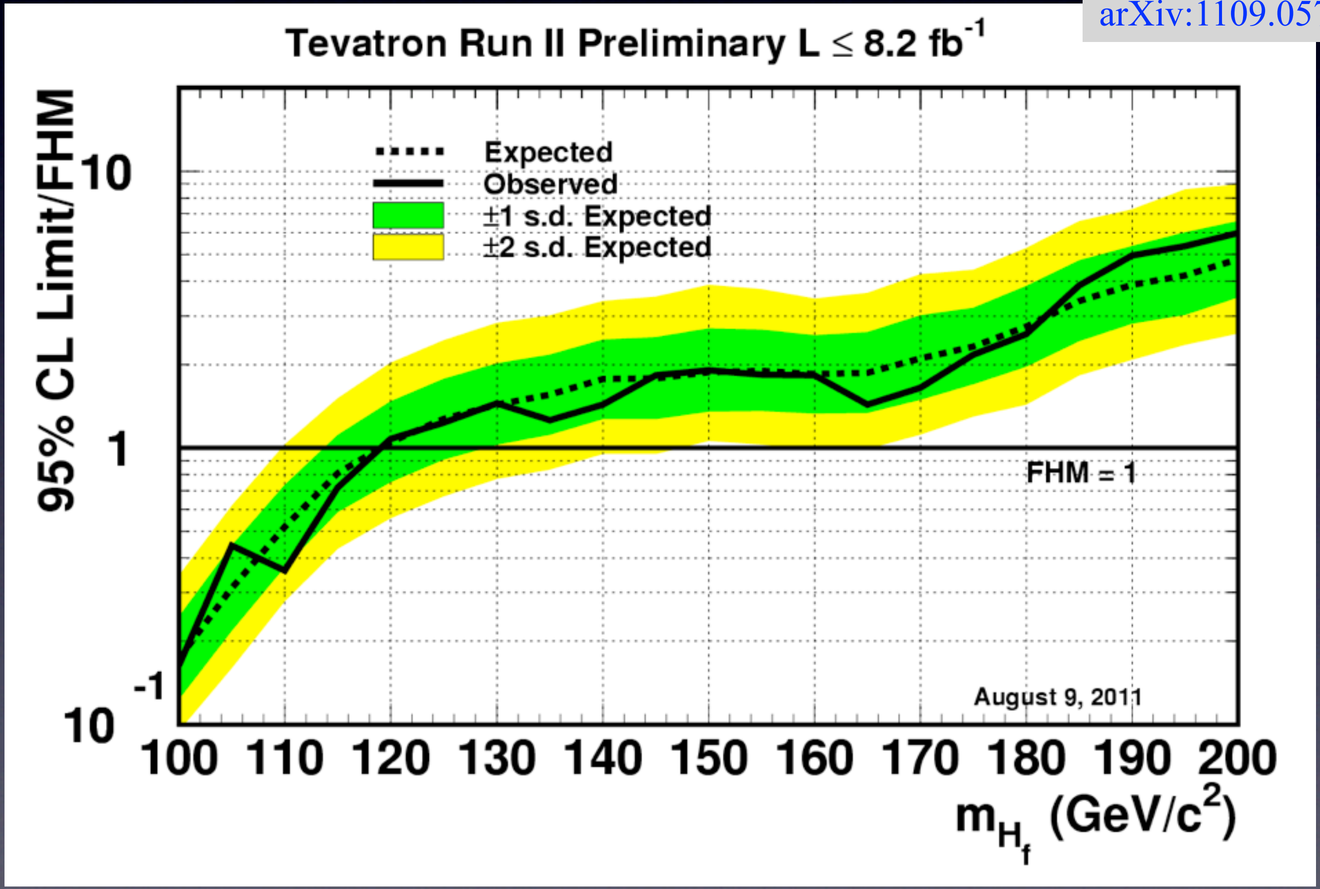


125 Gev Higgs would imply no SM-like 4th generation

Fermiophobic Higgs

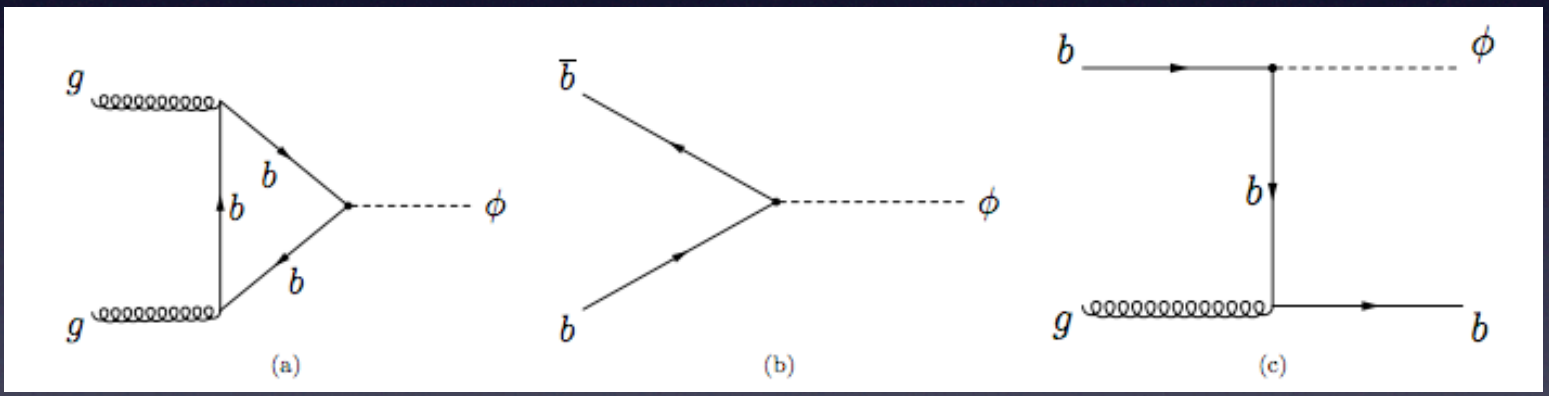
- Evidence for $H \rightarrow bb$ reduces urgency of these searches
- Most powerful mode is $H \rightarrow \gamma\gamma$, but $H \rightarrow WW$ also contributes
- Combination of CDF and DØ searches:

arXiv:1109.0576 [hep-ex]



MSSM Higgs

- In MSSM, couplings of neutral Higgs to down-type fermions is proportional to tanβ
  - cross section scales as ~tan$^2\beta$
- Dominant decays at high tanβ are bb (90%) and $\tau\tau$ (10%)
- Production modes:

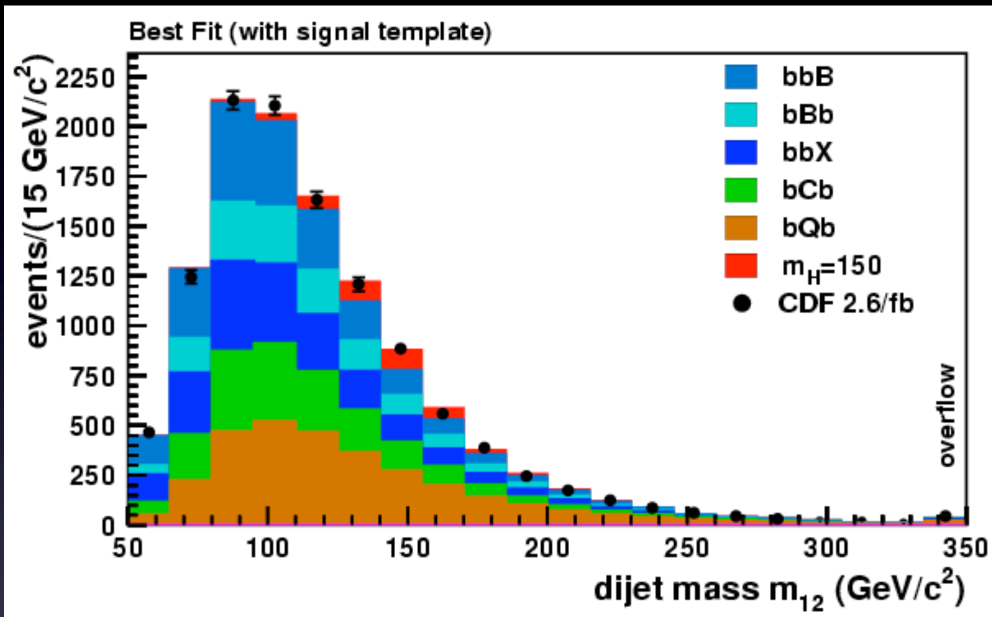


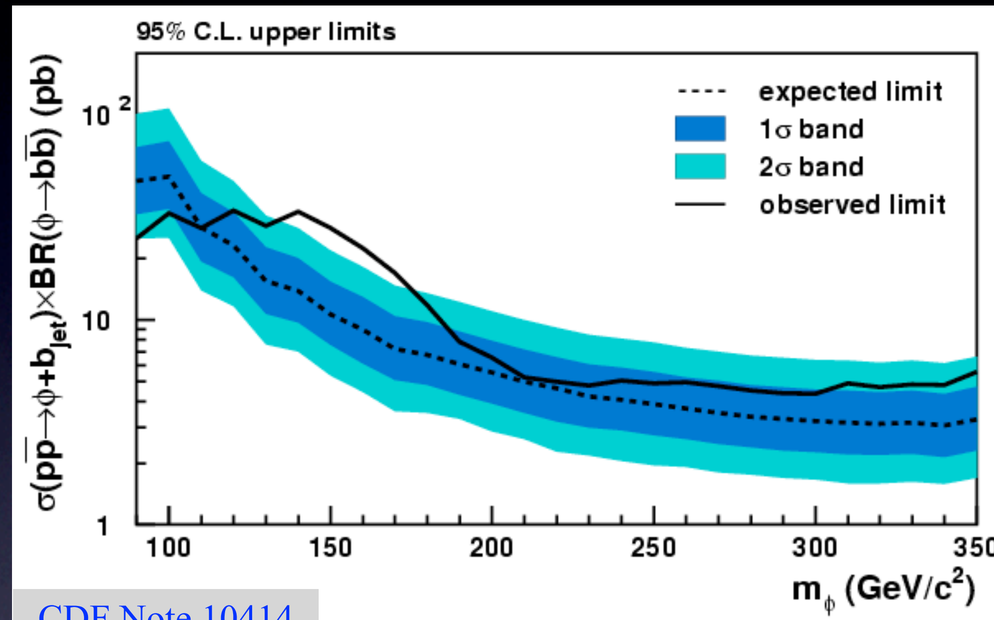
Extra final-state b quark reduces background

Tevatron has S/B advantage

CDF $b\varphi \rightarrow bbb$

- Large background from QCD production of multiple *b* jets is modeled with data-driven method



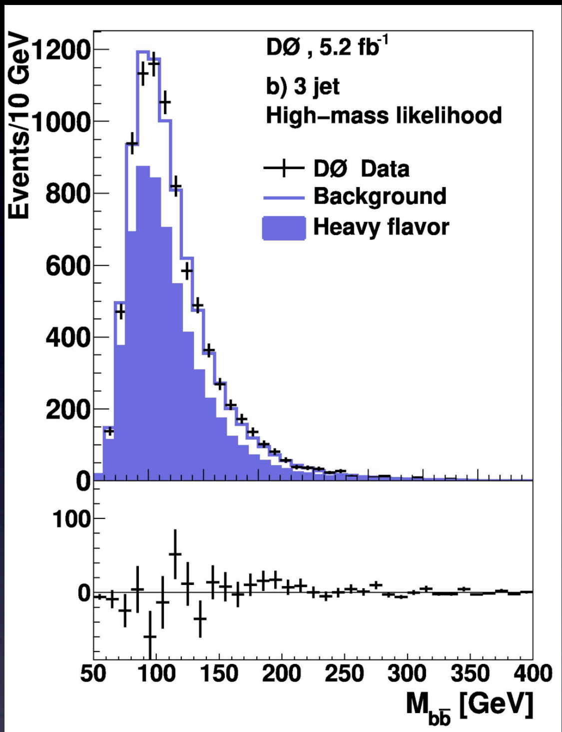


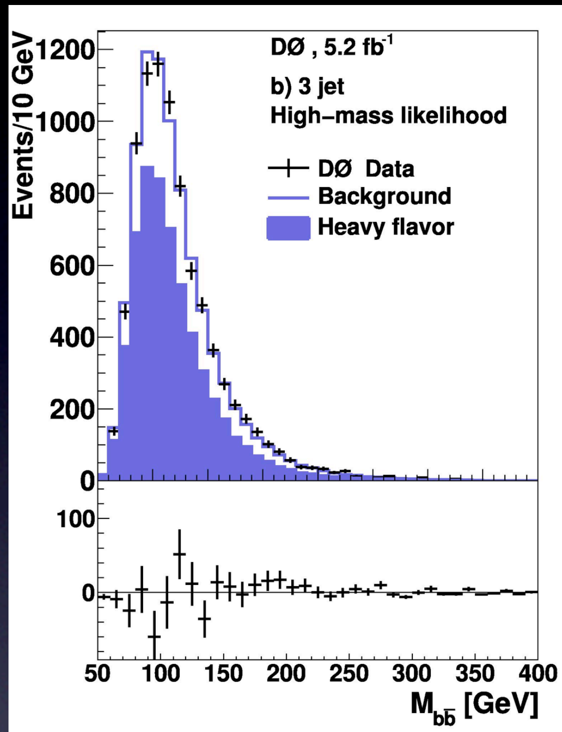
CDF Note 10414

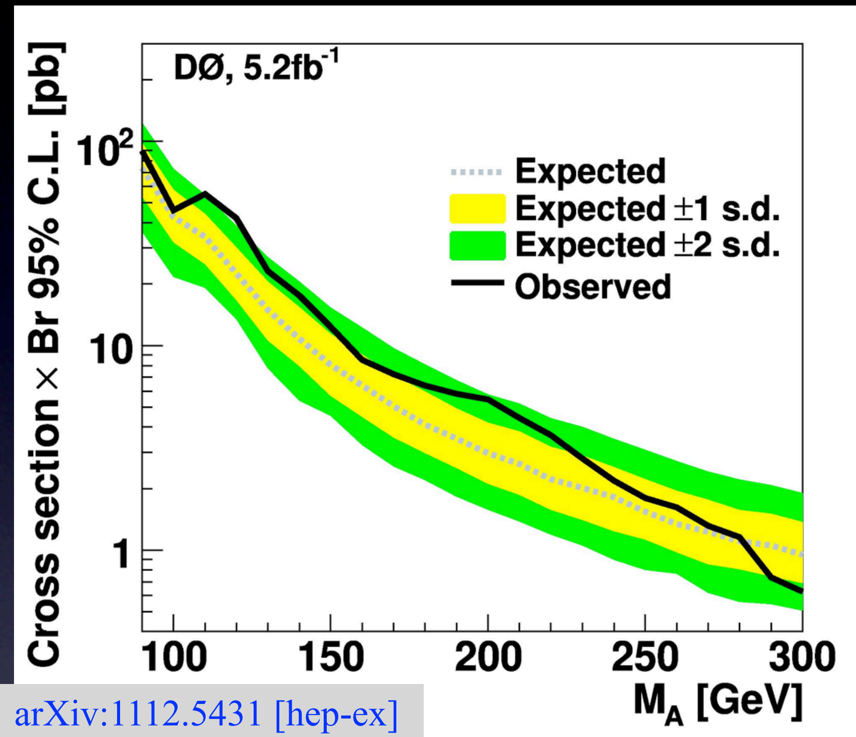
- Excess is observed for ~130 < m_φ < 160 GeV
  - maximum significance is 2.8σ at m_A = 150 GeV
  - with look-elsewhere effect, becomes 1.9σ
- Results are used to set limits in tanβ vs m_φ plane

DØ $b\varphi \rightarrow bbb$

- Separate discriminants used for low (<130 GeV) and high m_φ







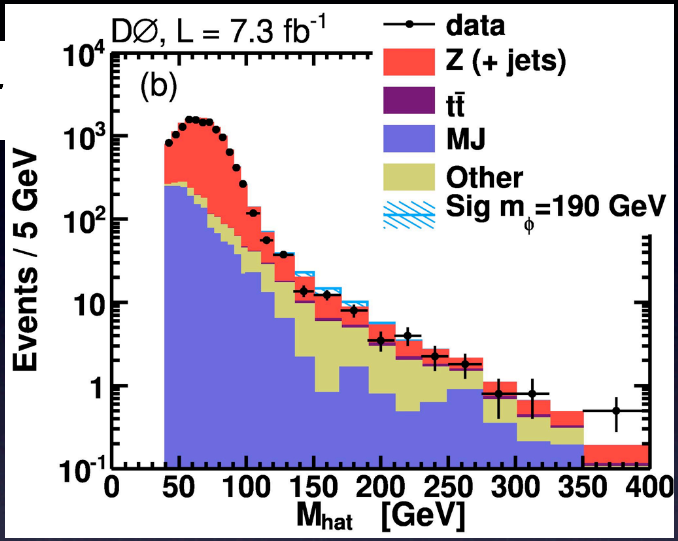
arXiv:1112.5431 [hep-ex]

- Largest excess is 2.5σ at m_φ=120 GeV
  - 2σ with look-elsewhere effect
- Model-dependent limits set

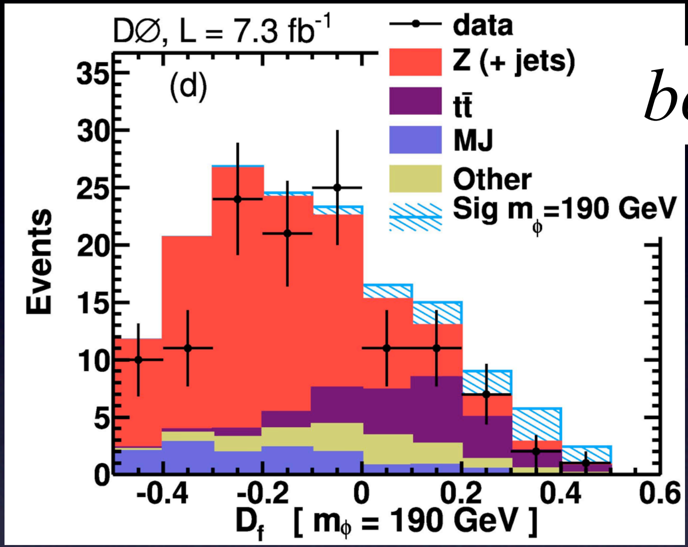
DØ MSSM Combination

- DØ combines the *bbb* search with searches for $\varphi\rightarrow\tau\tau$ and $b\varphi\rightarrow b\tau\tau$

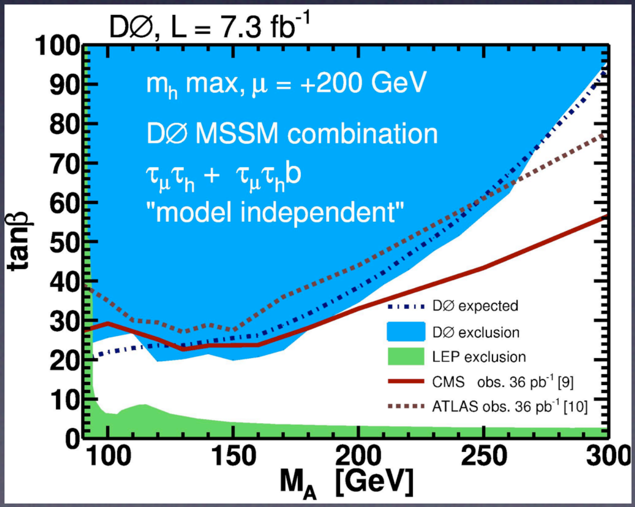
$\varphi\rightarrow\tau\tau$



$b\varphi\rightarrow b\tau\tau$



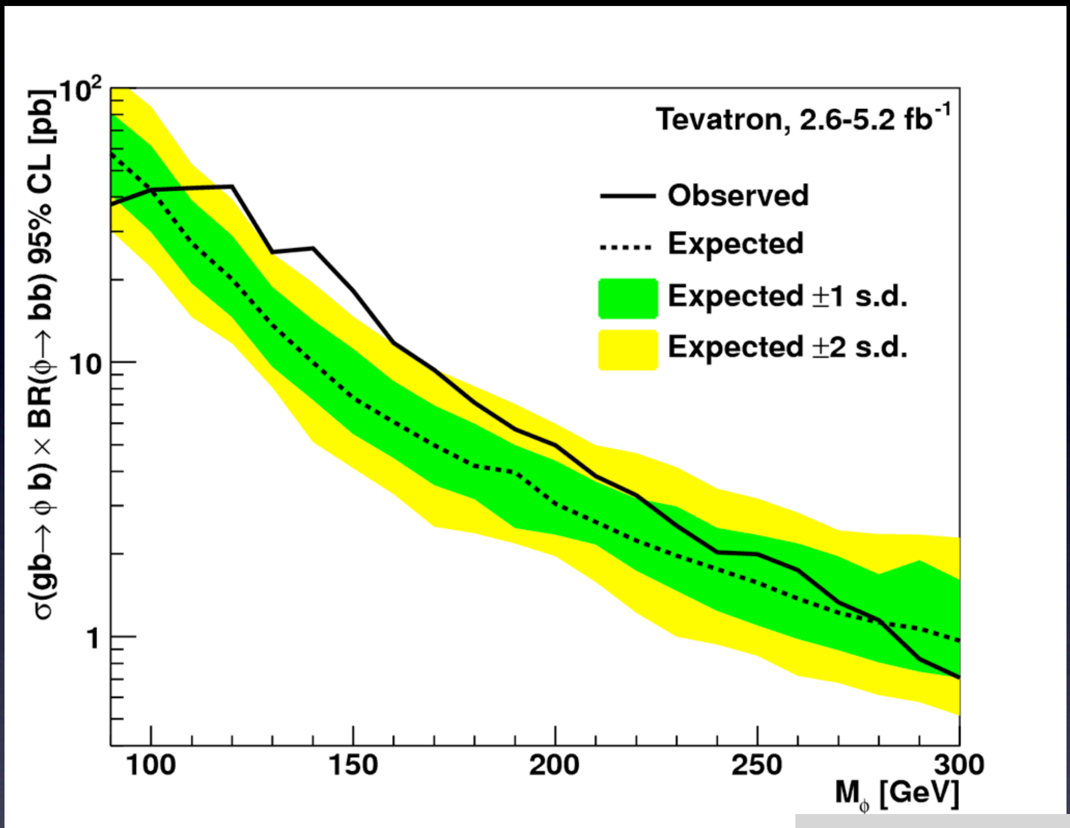
- Limits:

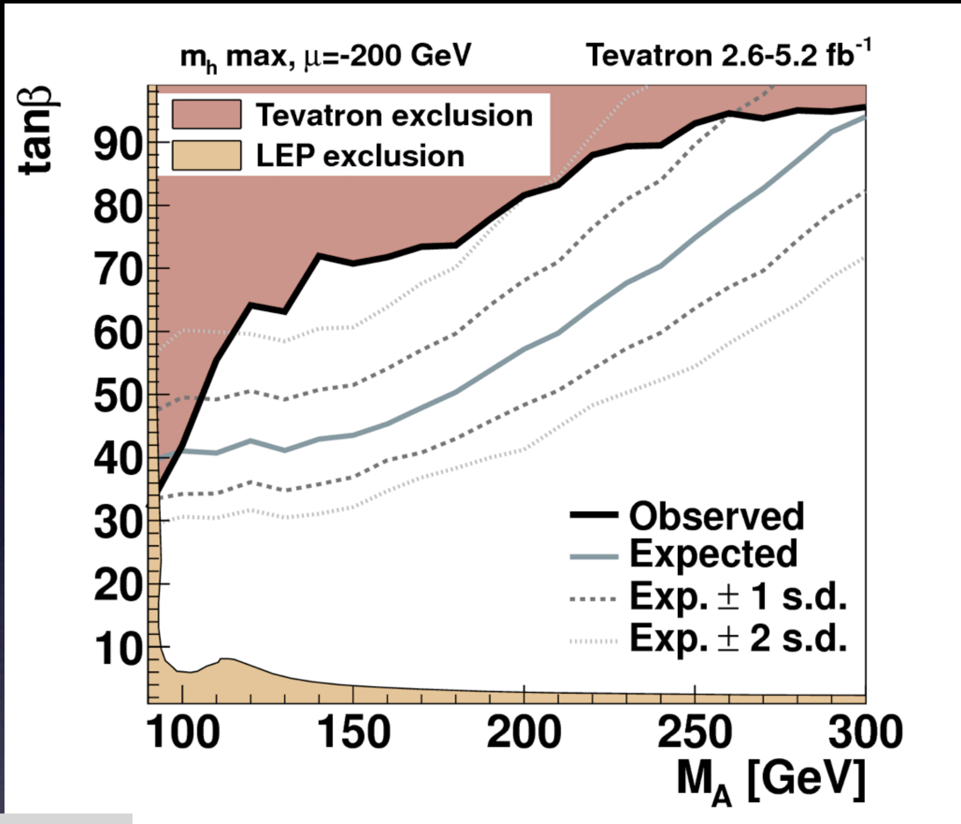


Phys. Lett. B **710**, 569 (2012),

Tevatron $b\varphi\rightarrow bbb$

- Combination of CDF and DØ $b\varphi\rightarrow bbb$ searches yields:



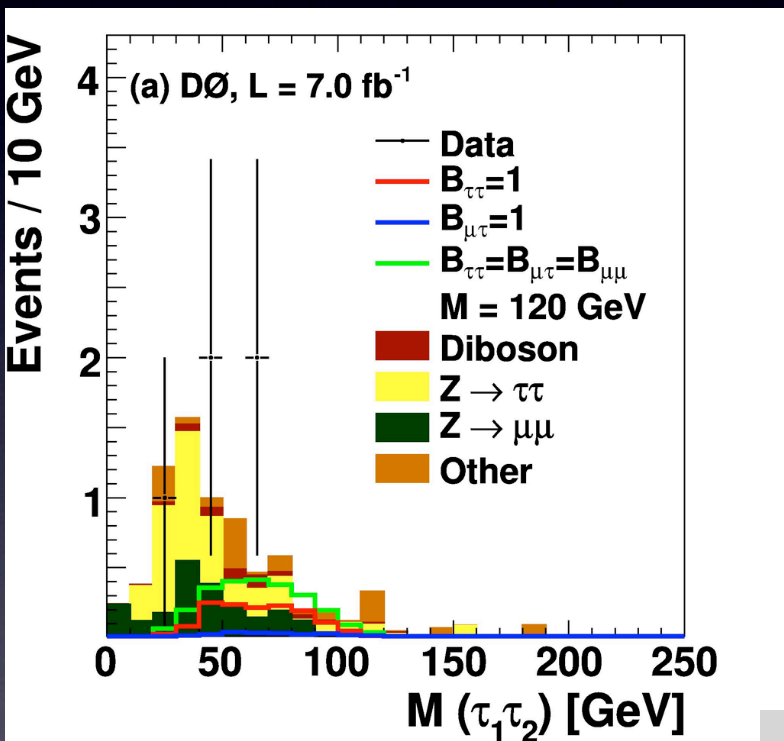


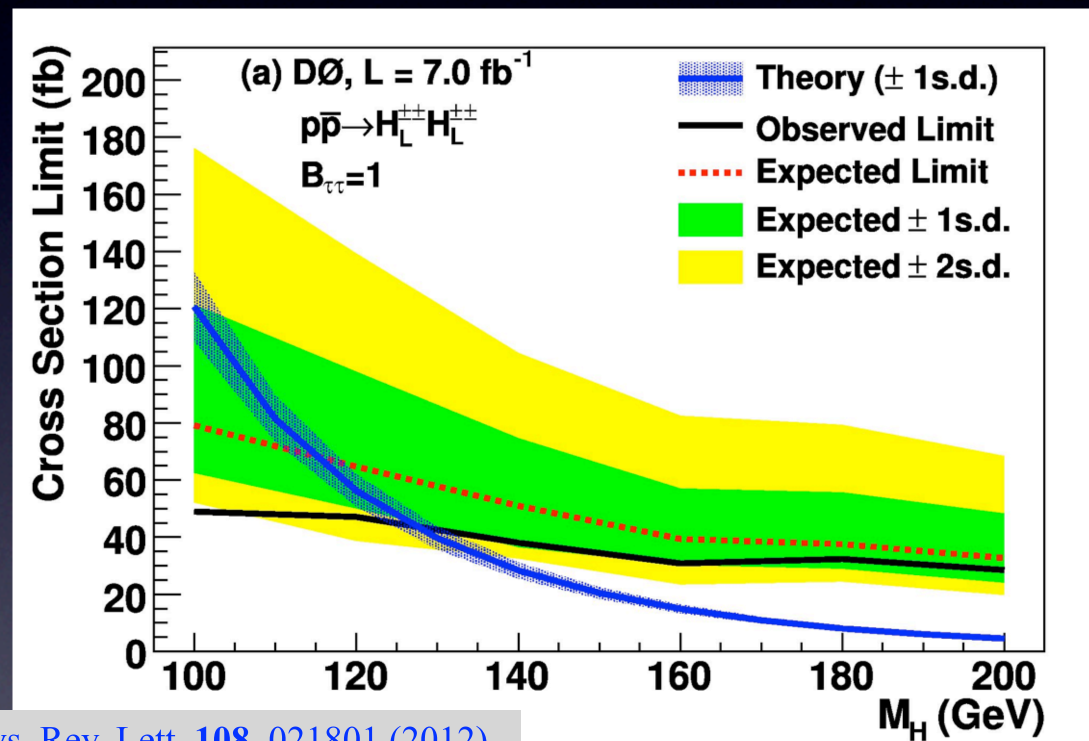
arXiv:1207.2757 [hep-ex]

- Slight excesses in each experiment are not reinforced by combination
- Global significance remains 2σ

Doubly-charged Higgs

- Doubly-charged Higgs bosons appear in several extended Higgs sector models
- DØ searches for $p\bar{p} \rightarrow H^{++}H^{--} \rightarrow \ell^{+}\ell^{+}\tau^{-}\tau^{-}$



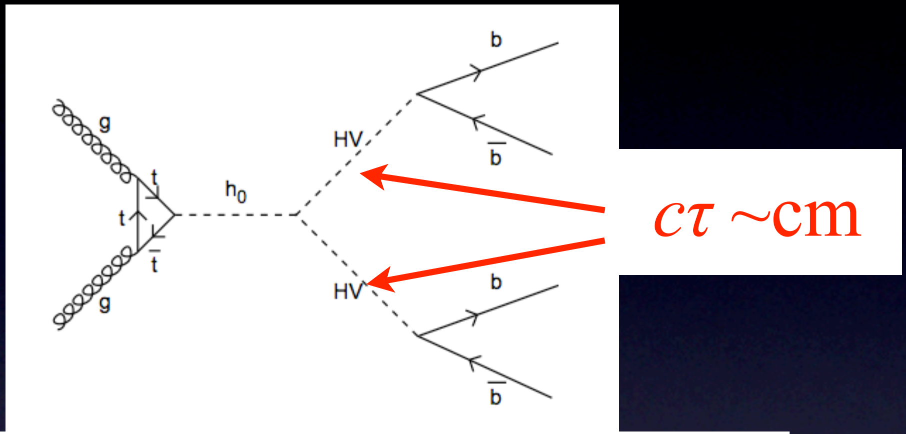


Phys. Rev. Lett. **108**, 021801 (2012)

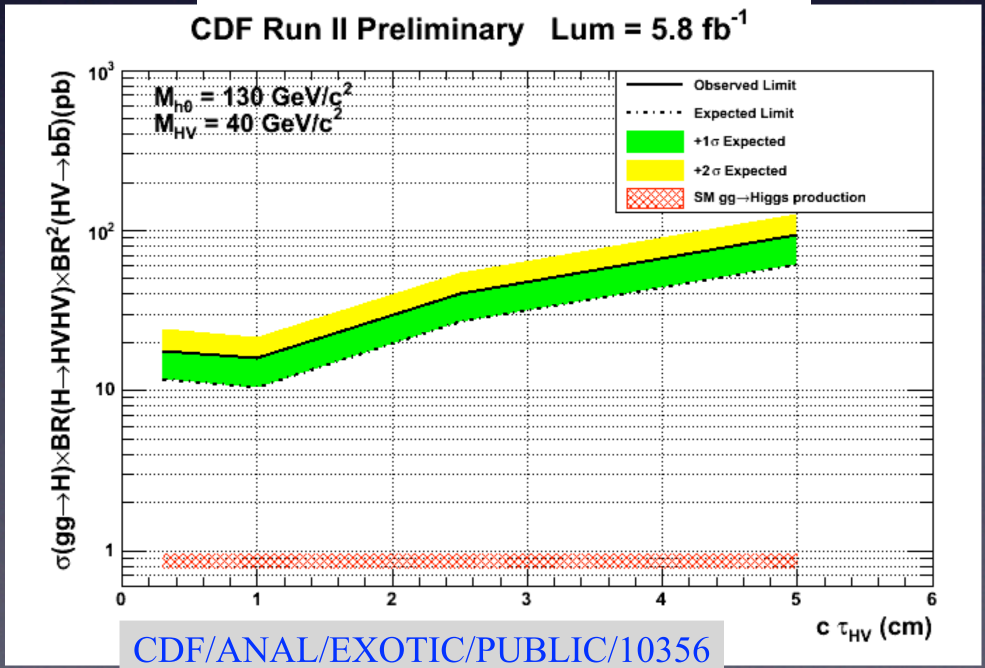
- No signal observed
  - M_{H++} mass limits depend on assumed couplings

Hidden Valley

- Hidden valley theories predict new class of particles that connect exotic and SM gauge sectors
  - Higgs couplings to these result in distinctive signatures



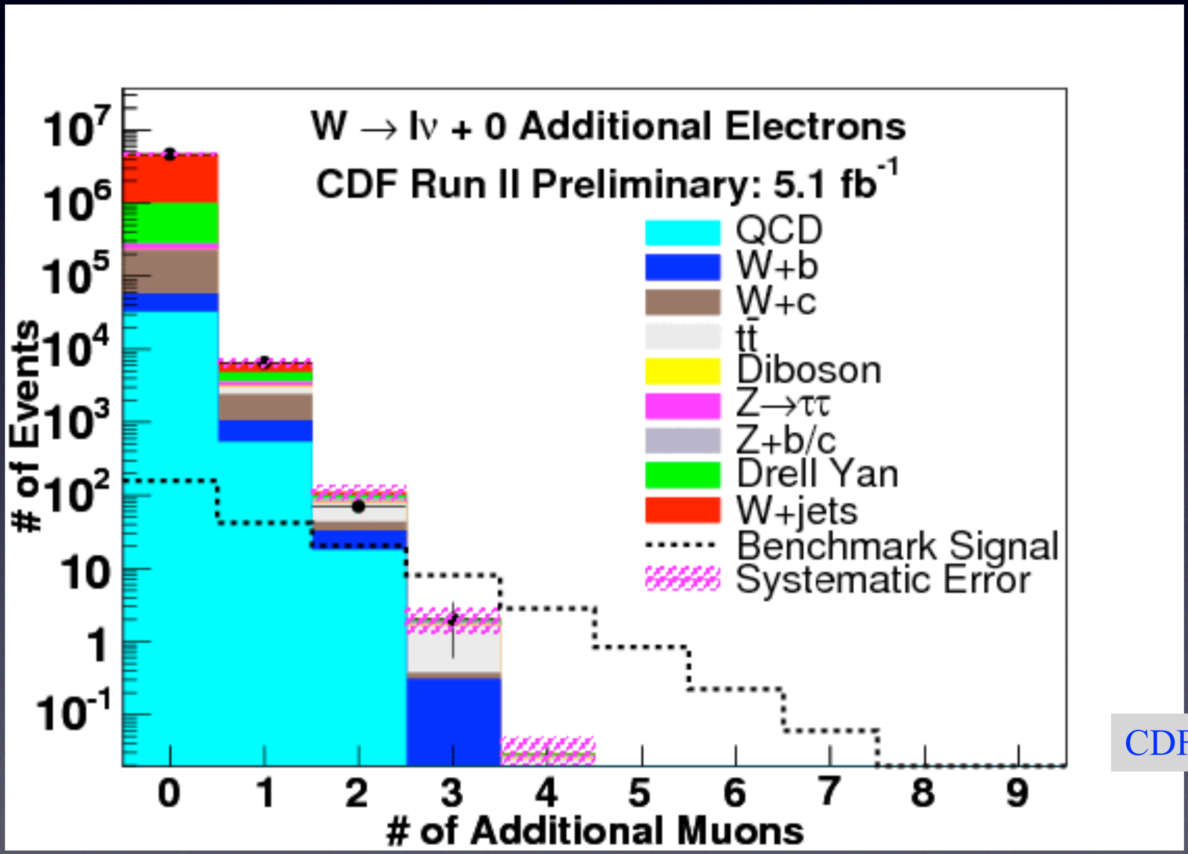
- CDF observes no excess in 4*b* final state
- Cross section limit vs. HV particle lifetime:



CDF/ANAL/EXOTIC/PUBLIC/10356

W/Z + Leptons

- In some Hidden Valley models, Higgs decay can result in a large number of soft leptons
  - leptons can have p_T as low as 2 GeV and can form "lepton jets"



$\sigma < 112$ fb
@95% C.L.

CDF/ANAL/EXOTIC/PUBLIC/10526

Summary

- CDF and DØ have searched for the Higgs boson
  - in a wide variety of decay channels
  - under both SM and new physics hypotheses
- Most of these searches use the entire Run II data sample
  - and our best analysis techniques
- In most cases our results are now superseded by the LHC
- The highlight is 3σ evidence for $H \rightarrow bb$
  - the best indication to date that the newly-found boson couples to fermions