



D0 Higgs Results and Tevatron Higgs Combination

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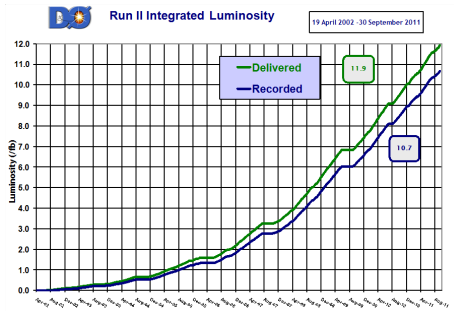
July 23rd 2012

On behalf of the CDF and D0 collaborations

Outline

- 1 Introduction
- 2 Higgs Introduction
- 3 D0 Higgs Results: Channel by Channel
- 4 D0 Higgs Combination
- 5 Tevatron Higgs Combination
- 6 Conclusions

Tevatron Run II



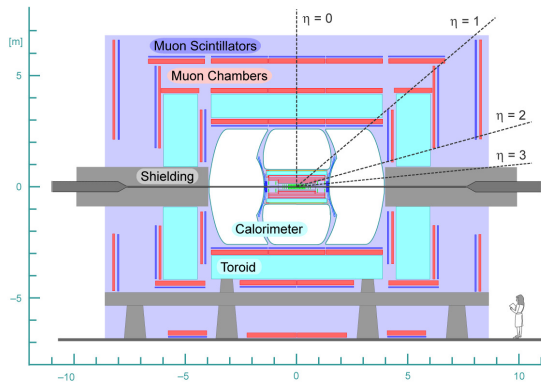
$p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV

Over 10 years, more than 10 fb^{-1} recorded per experiment

Timeline

For past 10 years, the Tevatron was essentially the only running high energy collider capable of directly exploring high energy phenomena. Now only the LHC has this privilege for the near future.

D0 Detector



D0 $B=1.9T$, $R = 0.5m$

Technically - could have kept going for 3 more years

Putting things in context

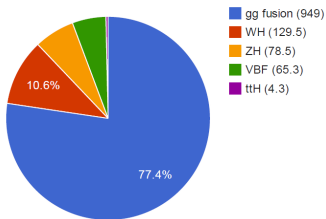
- Experiments (direct and indirect) have been constraining the SM Higgs habitable zone for decades
- As you all know and were very recently reminded, the latest LHC results indicate the presence of a new particle consistent with the Standard Model Higgs boson with a mass near 125 GeV
- The LHC results together with prior results principally from LEP, SLC and Tevatron constrain the SM Higgs should it exist to a narrow ≈ 5 GeV wide mass region near 125 GeV
- Evidence is strongest in the $\gamma\gamma$ and 4-leptons (ZZ^*) decay modes
- The Tevatron experiments have been searching for the Higgs for the last decade, and now have close to final results to report which provide an independent and complementary test of this new phenomenon in the 100 - 200 GeV mass range and in particular near 125 GeV
- Tevatron is sensitive to different decay modes and production mechanisms (for more details see Michelle Stancari's talk)

D0 Higgs Searches

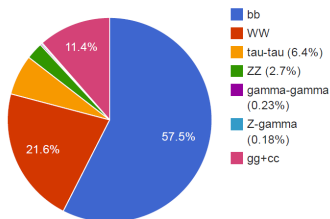
D0 Higgs Searches

Many channels are searched motivated by m_H in the 100-200 GeV mass range.

125 GeV SM Higgs Tevatron Cross-Sections (fb)



125 GeV SM Higgs Branching Ratios (%)



$m_H = 125$ GeV

Relative sensitivities (in expected exclusion rate) of some of the channels

Channel	R_{95}^{exp}	Channel	R_{95}^{exp}
$H \rightarrow WW \rightarrow \ell^+ \ell^- \cancel{E}_T$	3.6	$H \rightarrow \gamma\gamma$	8.2
$ZH \rightarrow \nu\nu b\bar{b}$	3.9	3ℓ (WH, ZH)	11.1
$WH \rightarrow \ell\nu b\bar{b}$	4.1	$e^\pm \mu^\pm$ (WH)	11.6
$ZH \rightarrow \ell^+ \ell^- b\bar{b}$	5.1	$\tau\tau$	12.8

Quantifying Evidence For/Against a Signal

Hypotheses

SM Higgs search involves testing two hypotheses

- \mathcal{H}_b (Null) : Only SM background events
- \mathcal{H}_{s+b} (Signal) : Presence of SM Higgs and SM background events

Likelihood Ratio

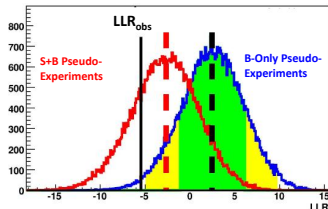
Form a (log) likelihood ratio test-statistic to compare the two hypotheses

$$\text{LLR} = -2 \log \frac{p(\text{data}|\mathcal{H}_{s+b})}{p(\text{data}|\mathcal{H}_b)}$$

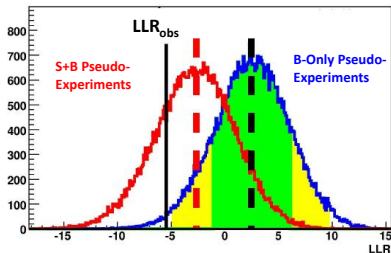
Define $\text{CL}_S \equiv \text{CL}_{s+b}/\text{CL}_b$ where

$$\text{CL}_{s+b} = p(\text{LLR} \geq \text{LLR}_{\text{obs}}|\mathcal{H}_{s+b})$$

$$\text{CL}_b = p(\text{LLR} \geq \text{LLR}_{\text{obs}}|\mathcal{H}_b)$$

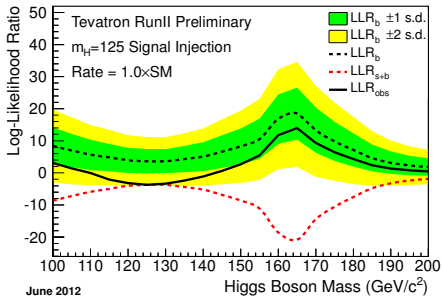


What To Expect With Log-Likelihood Ratio



LLR Distribution

- Pseudo-experiments with \mathcal{H}_b true
- Pseudo-experiments with \mathcal{H}_{s+b} true
- Example observed value of LLR_{obs}



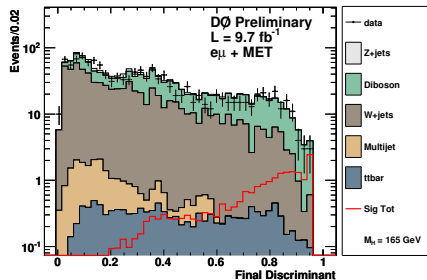
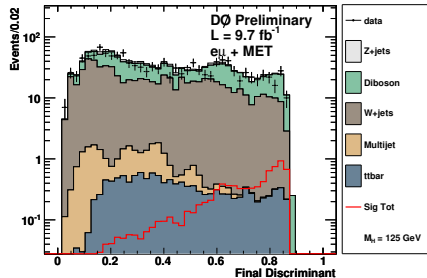
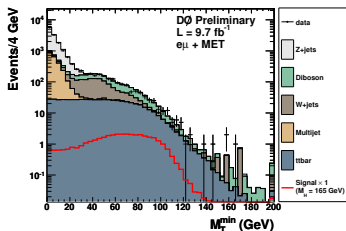
Expectations

- Dashed black and red lines show median LLR values expected under both hypotheses vs m_H
- Sensitivity greatest when these two lines are most separated
- Black curve: median expected outcome if 125 GeV SM Higgs present
- Mass resolution ≈ 10 -15 GeV - so the median LLR_{obs} differs from median LLR_b for a range of m_H hypotheses

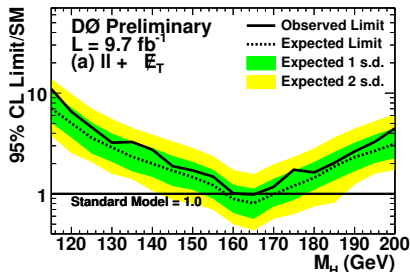
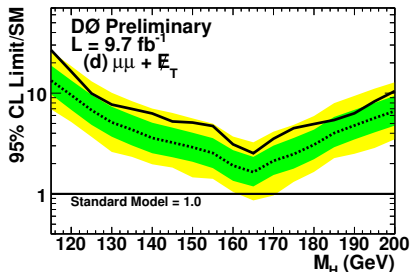
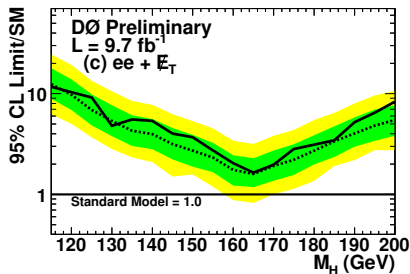
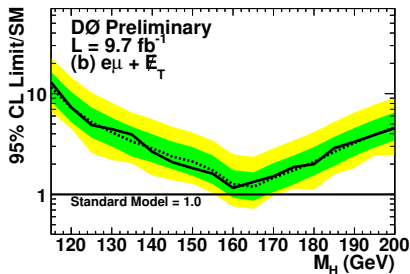
$$H \rightarrow WW \rightarrow l_1^+ l_2^- \cancel{E}_T (l_i = e \text{ or } \mu)$$

Event Selections

- Selections for ee , $\mu\mu$ and $e\mu$
- Main backgrounds DY and WW
- Overview: preselection, DY rejection, BDT final discriminants
- Separate in 0-jet, 1-jet, 2-jet bins
- $e\mu$ channel has best signal ($\times 2$) and lowest background
- Plots from $e\mu$ selection



$H \rightarrow WW \rightarrow l_1^+ l_2^- \cancel{E}_T$ ($l_i = e$ or μ) Upper Limits

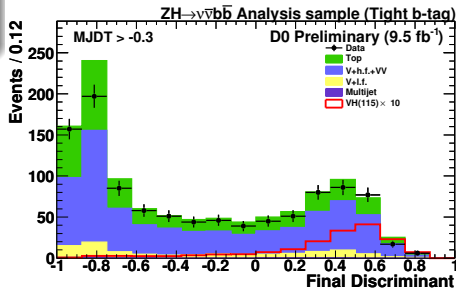
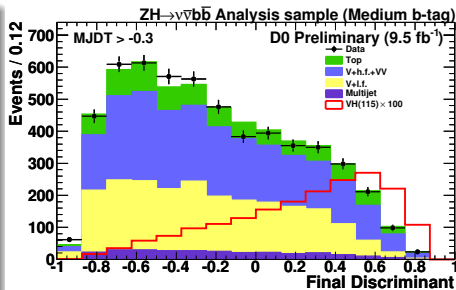
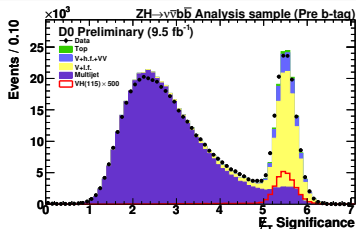


95% CL upper limit: 4.6 (3.6) σ_{SM} observed (expected) at 125 GeV

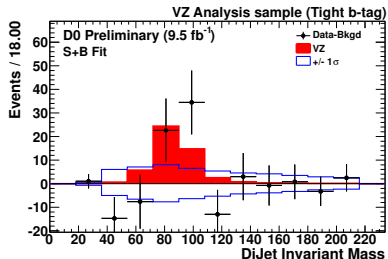
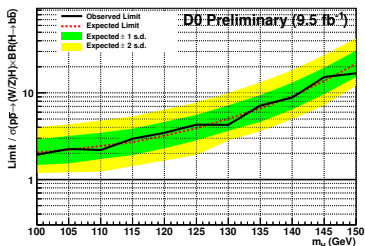
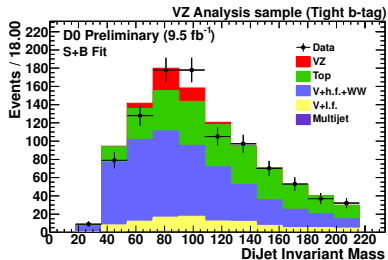
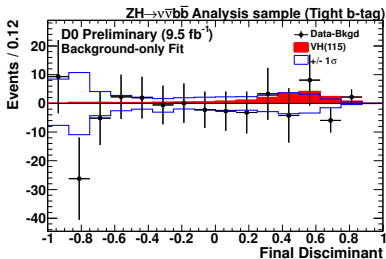
ZH $\rightarrow \nu\nu b\bar{b}$ Channel

Event Selection

- Pair of b-jets + \cancel{E}_T
- Designed for ZH. Also sensitive to WH where ℓ from W unidentified
- Backgrounds: V + heavy-flavor jets, top quarks, multi-jet (MJ)
- Control samples for background modeling (lepton+jets and MJ)
- Use B-tagging and MVAs. Validate with analysis of VZ



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



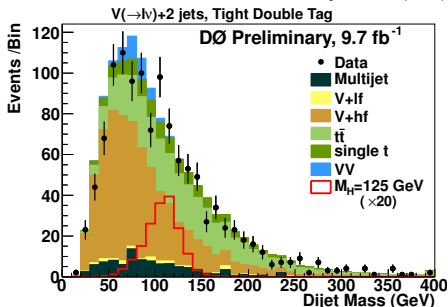
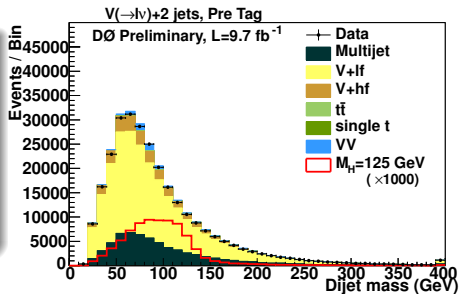
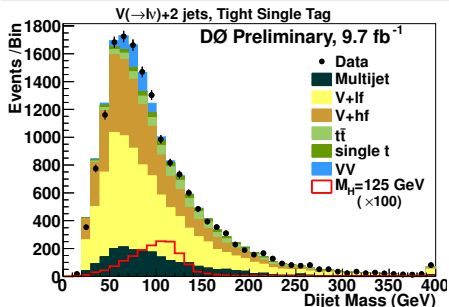
4.3 (3.9) σ_{SM} observed (expected) at 125 GeV

Measure WZ+ZZ cross-section
0.94 \pm 0.31 \pm 0.34 times expectation

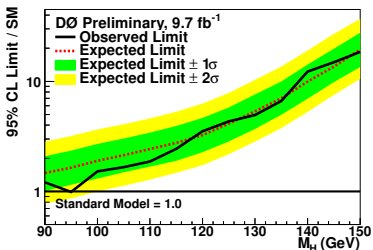
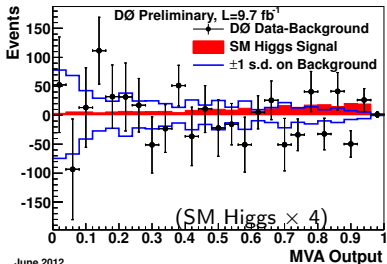
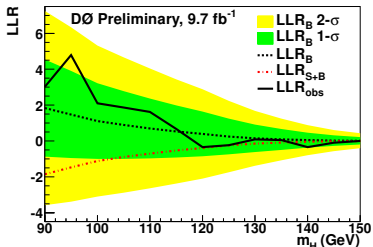
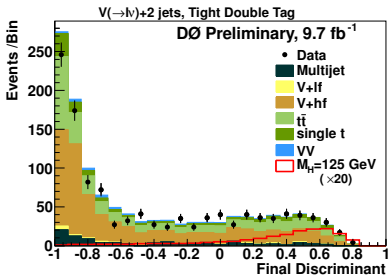
WH \rightarrow $l\nu b\bar{b}$ Channel

Event Selection

- $l + 2\text{-jets } (\geq 1 \text{ b-tagged}) + \cancel{E}_T$
- T-ST, (L,M,T)-DT b-tag categories
- Backgrounds: V + heavy-flavor jets, top quarks
- 2,3,4-jet categories



WH \rightarrow $l\nu b\bar{b}$ Channel Limits

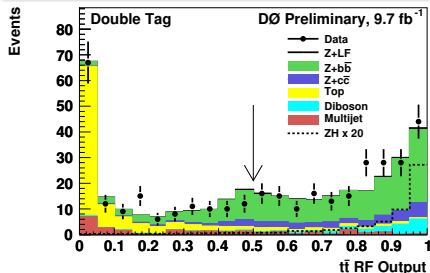


95% CL limit of $4.5 \sigma_{SM}$ observed cf $4.1 \sigma_{SM}$ expected at 125 GeV

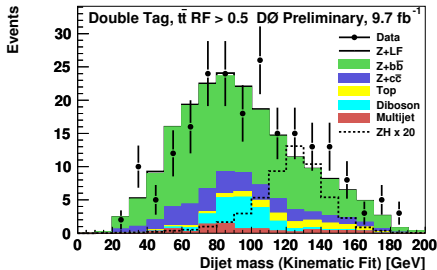
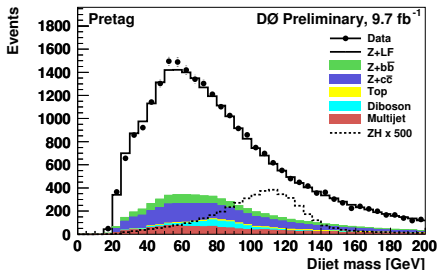
ZH \rightarrow $llb\bar{b}$ Channel

Event Selection

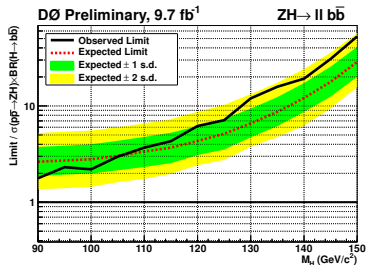
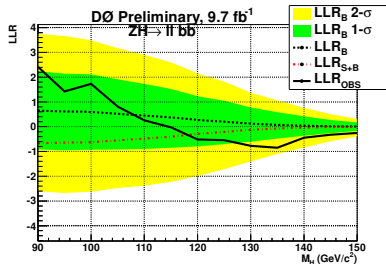
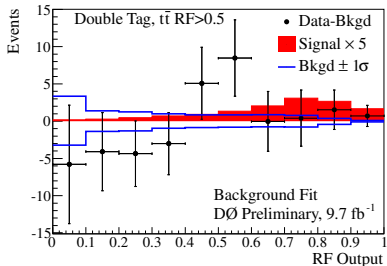
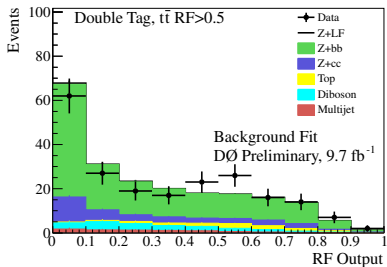
- 2-leptons + 2-jets (≥ 1 b-tagged)
- Constrain ll to m_Z and $llb\bar{b}$ p_T
- Backgrounds: Z + heavy-flavor jets, top quarks
- Use $t\bar{t}$ MVA to split in $t\bar{t}$ -depleted and $t\bar{t}$ -rich subsamples



Signal samples with $m_H = 125$ GeV



ZH \rightarrow $llb\bar{b}$ Channel Limits

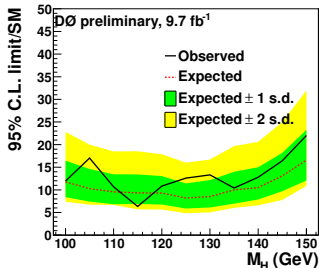
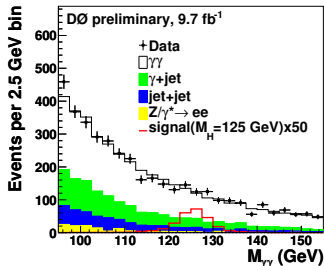
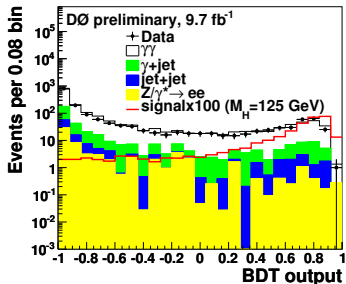


95% CL limit of 7.1 σ_{SM} observed cf 5.1 σ_{SM} expected at 125 GeV

Inclusive $H \rightarrow \gamma\gamma$ Channel

Event Selection

- ≥ 2 photons with $E_T > 25$ GeV
- Identify photons from jet fakes
- Measure backgrounds from $\gamma\gamma$, γ -jet, jet-jet
- Use separate kinematic BDT for photon and jet-dominated samples

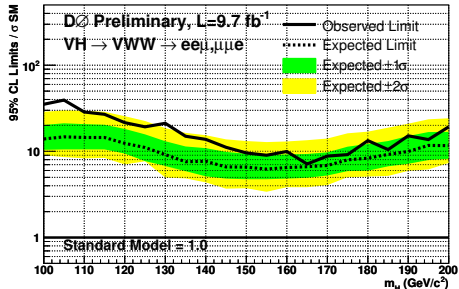


12.6 (8.2) σ_{SM} observed (expected) at 125 GeV

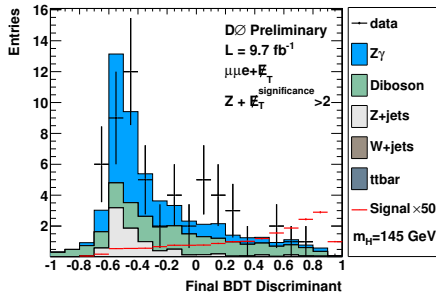
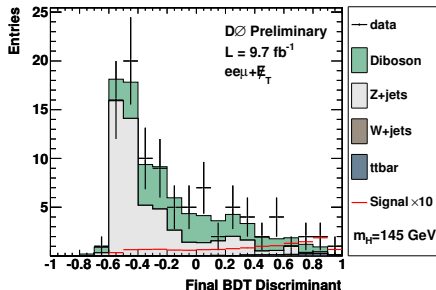
Trileptons Channel. WH, ZH, H. Leading to $lllX$

Event Selection

- Mainly for WH, ZH with $H \rightarrow VV$
- Focus on $e\mu$, $\mu\mu$ channels
- Backgrounds: WZ, ZZ, Z+jets, $Z\gamma$
- Use BDTs to exploit signal characteristics (3 in $\mu\mu$ channel)



19.3 (11.1) σ_{SM} observed (expected) @ 125 GeV



D0 Channel Summary

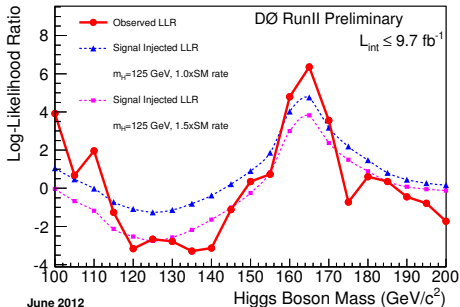
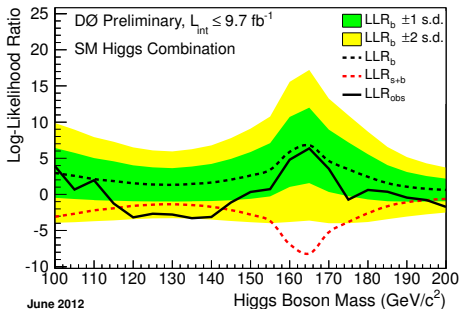
Results for $m_H = 125$ GeV

All main channels find signal-like excesses in data for $m_H = 125$ GeV. No individual channel by itself shows high significance.

Channel	R_{95}^{exp}	R_{95}^{obs}
$H \rightarrow WW \rightarrow \ell^+ \ell^- \cancel{E}_T$	3.6	4.6
$ZH \rightarrow \nu\nu b\bar{b}$	3.9	4.3
$WH \rightarrow \ell\nu b\bar{b}$	4.1	4.5
$ZH \rightarrow \ell^+ \ell^- b\bar{b}$	5.1	7.1
$H \rightarrow \gamma\gamma$	8.2	12.6
3 ℓ (WH, ZH)	11.1	19.3
$e^\pm \mu^\pm$ (WH)	11.6	7.8
$\tau\tau$	12.8	15.7
Total	1.70	2.94

Next: D0 combination plots for all Higgs masses.

D0 Higgs Combination



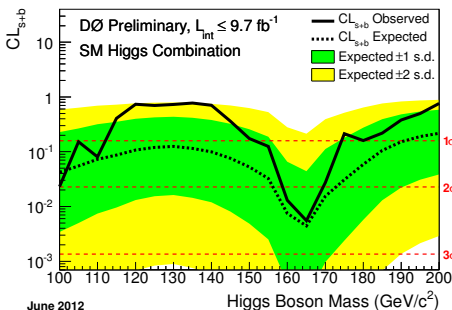
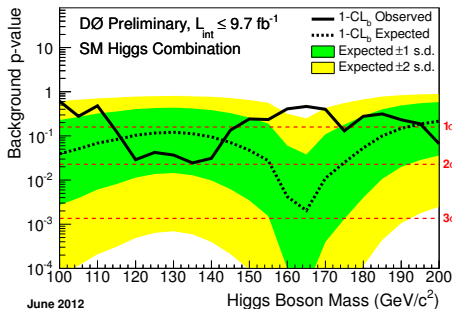
D0 Result

Data is more consistent with the expected signal hypothesis for SM Higgs masses in the 110-140 GeV range than the background-only hypothesis

Signal Injection Test

- Add $m_H = 125 \text{ GeV}$ signal events with SM Higgs cross-section and BRs
- Blue curve shows median expected outcome if a SM Higgs of 125 GeV is present
- Purple curve shows median expected outcome if a SM-like Higgs of 125 GeV is present with 1.5 times SM rate

Hypothesis Test Results (Focussing on Low Mass)



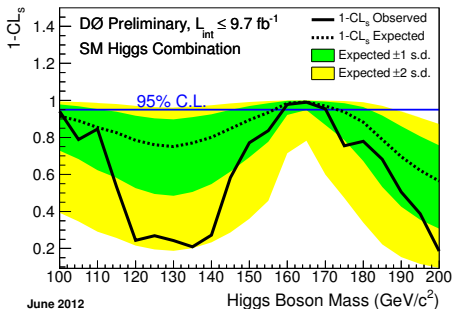
Inconsistent with Background Hypothesis

- Black: Probability for B to fluctuate up to as signal-like or more an observed outcome
- Background p-value = 4% for $m_H = 125 \text{ GeV}$
- Dashed: Median expected B p-value if S+B hypothesis true

Consistent with Signal Hypothesis

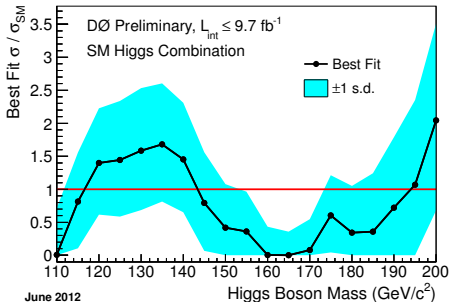
- Black: 1 - probability for S+B to fluctuate up to as signal-like or more an observed outcome
- Dashed: Median expected CL_{S+B} if B is true

Mass Limits and Signal Strength



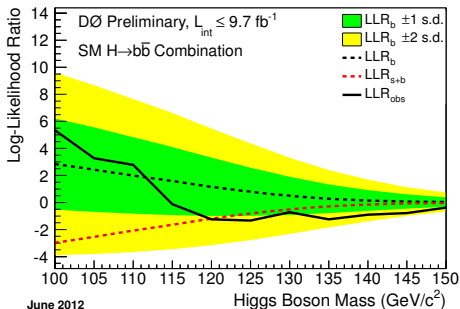
Exclusion Strength

- Black: D0 Data exclude SM Higgs with masses from 159-170 GeV at at least 95% CL
- In the 115-145 GeV region, the data favor the signal hypothesis

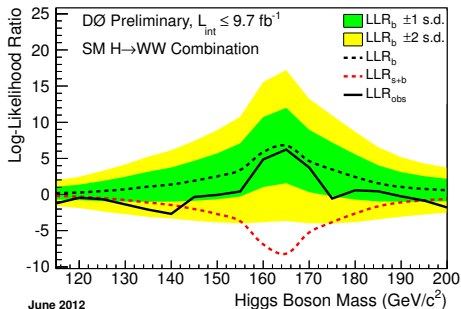


Signal Strength

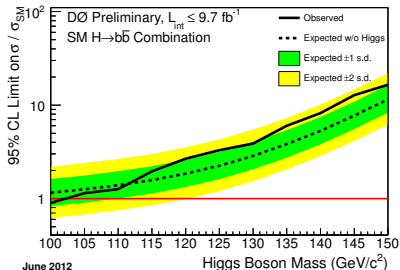
- Best fit signal strength (with $\pm 1\sigma$ uncertainty band)
- Consistent with SM Higgs at low mass

Decays to $b\bar{b}$. Decays to WW

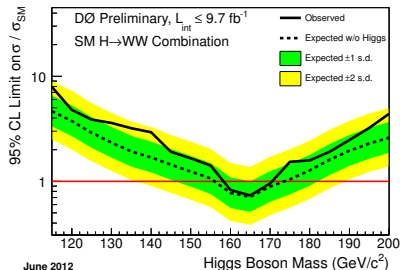
June 2012



June 2012

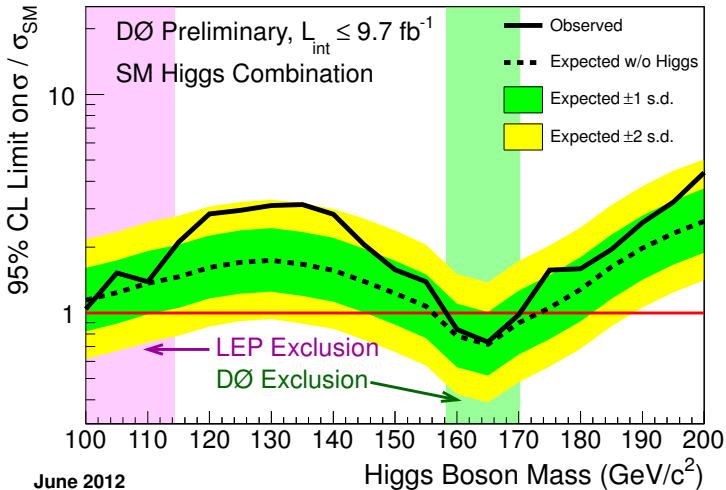


June 2012



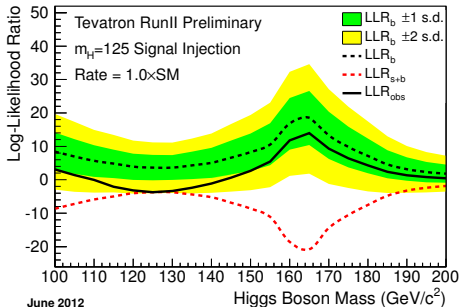
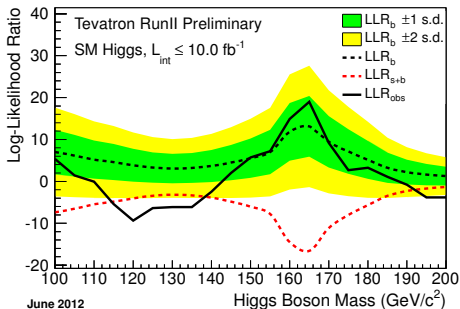
June 2012

D0 Summary Plot



D0 data does not exclude a SM Higgs with mass near 125 GeV (expected 95% CL limit = $1.7 \sigma_{\text{SM}}$ for B-hypothesis). Overall background-only p-value = 4%

Log-Likelihood Ratio



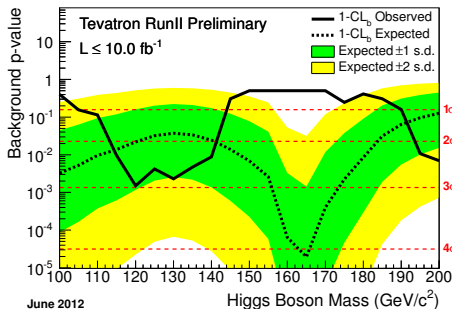
Tevatron Result

Data is much more consistent with the expected signal hypothesis for SM Higgs masses in the 110-140 GeV range than the background-only hypothesis

Signal Injection Test

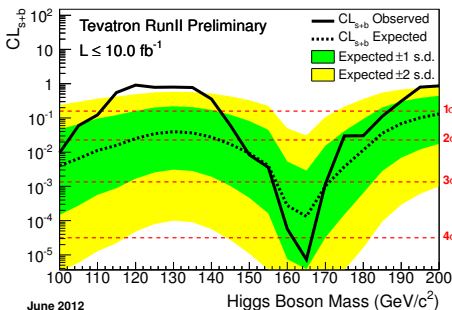
- Add $m_H = 125 \text{ GeV}$ signal events with SM Higgs cross-section and BRs
- Solid black curve shows median expected outcome if a SM Higgs of 125 GeV is present
- Mass resolution typically 10-15 GeV - so the median LLR_{obs} differs significantly from the median LLR_b for a range of m_H hypotheses

Hypothesis Test Results (Focussing on Low Mass)



Inconsistent with Background Hypothesis

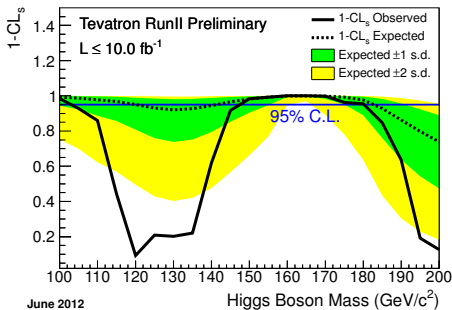
- Black: Probability for B to fluctuate up to as signal-like or more an observed outcome
- Background p-value = 0.4% for $m_H = 125 \text{ GeV}$
- Dashed: Median expected B p-value if S+B hypothesis true



Consistent with Signal Hypothesis

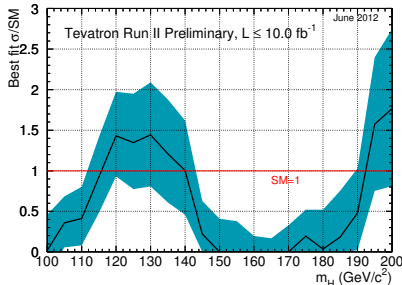
- Black: 1 - probability for S+B to fluctuate up to as signal-like or more an observed outcome
- Dashed: Median expected CL_{S+B} if B is true

Mass Limits and Signal Strength



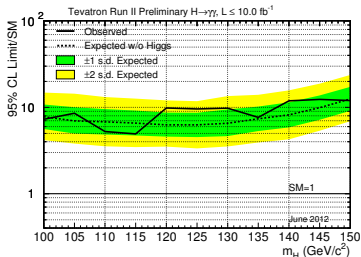
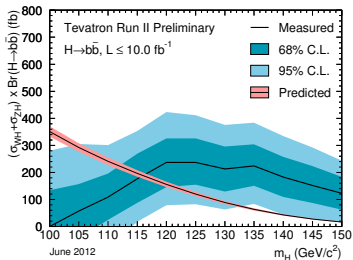
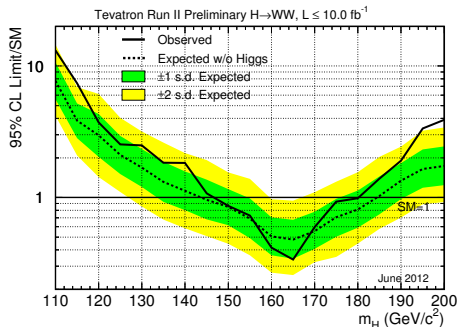
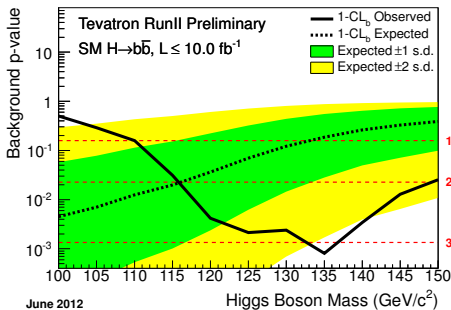
Exclusion Strength

- Black: Data exclude SM Higgs with masses in the ranges 100-103 and 147-180 GeV at at least 95% CL
- In the 110-140 GeV region, where there is sensitivity to exclude at around 95% CL, the signal-like excess in the data precludes setting useful limits

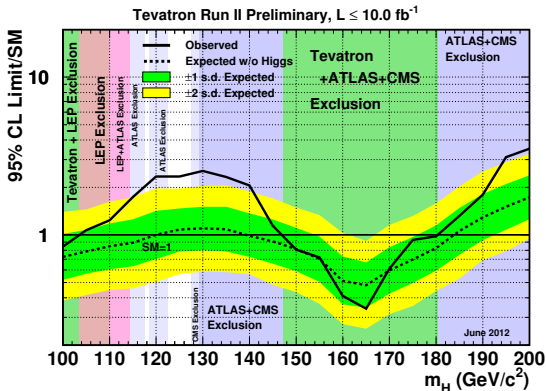


Signal Strength

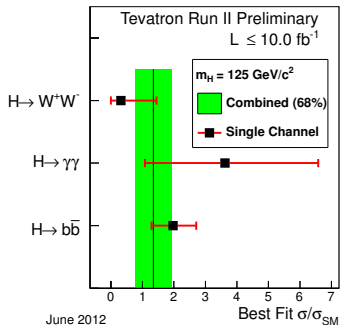
- Best fit signal strength (with $\pm 1\sigma$ uncertainty band)
- Consistent with SM Higgs (115-140 GeV)

Decays to $b\bar{b}$. Decays to WW . Decays to $\gamma\gamma$ 

Summary Plot



Tevatron data does not exclude a SM Higgs with mass near 125 GeV (expected 95% CL limit = $1.08 \sigma_{SM}$ for B-hypothesis)



Data is consistent with expected decay modes of 125 GeV SM Higgs including decay to $b\bar{b}$.
Overall background-only p-value = 0.4%.

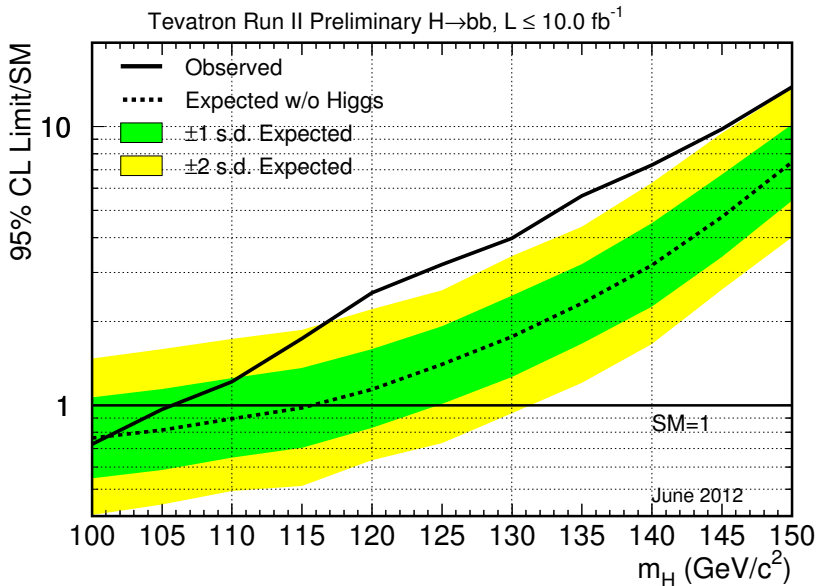
Concluding Remarks

Summary

- The RunII era of the Tevatron experiments' data-taking is over
- Close to final results from D0 indicate an excess of events at “low-mass” more consistent with SM Higgs hypothesis than background-only - with contributing indications in several channels
- Background fluctuation probability for $m_H = 125$ GeV is 4% for D0.
- Combined results from Tevatron and CDF have 0.4% overall background fluctuation probability for $m_H = 125$ GeV
- Breakdown by channel is consistent with Standard Model Higgs
- In particular the data are consistent with a significant Higgs coupling to $b\bar{b}$ as expected if the Higgs is also responsible for fermion mass generation

Backup Slides

Tevatron combined $b\bar{b}$ limit



Higgs Couplings

Predicted in SM - but only starting to be explored.

