Higgs results from Tevatron

3^{rd} Annual Large Hadron Collider Physics Conference

Federico Sforza
on behalf of the CDF and D0 Collaborations

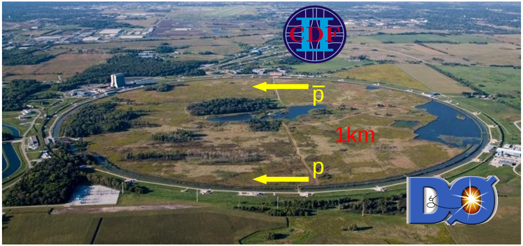
CERN

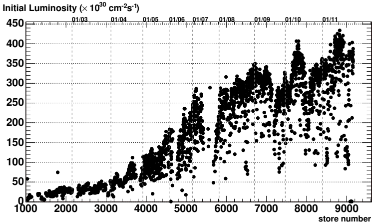
31 August 2015 - St. Petersburg

The Tevatron

Presented analyses use full Run II dataset, collected until September 2011:

Up to $\int \mathscr{L} \simeq 10\ \text{fb}^{-1}$, $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, per experiment ($\simeq 12\ \text{fb}^{-1}$ delivered)





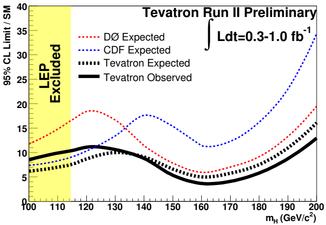
Store initial luminosity $\times 20$ increase over years

$\Rightarrow$ driven by abundance of anti-protons

Tevatron facts:

- First superconducting accelerator and largest *antimatter* source in the world
- Two instrumented collision points: **CDF & D0** experiments
- Run I and Run II cover almost 20 years of physics

A Very Brief History of Higgs Searches

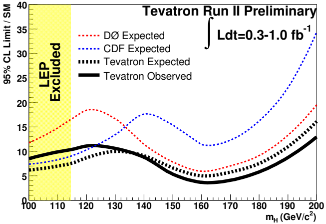


Tevatron role was unexpected several years ago:

- First Tevatron combination for SM Higgs 95% C.L.:

  $\Rightarrow$ 2006 analyses, 0.3–1 fb^{-1}
  (CDF 8384 & D0 5227 Notes)
- 95% exclusion sensitivity $\mathcal{O}(10)\times$SM
- *would need 100 fb^{-1} to reach 2σ sensitivity!*

A Very Brief History of Higgs Searches

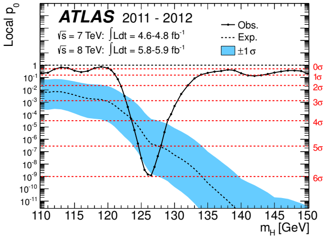


Tevatron role was unexpected several years ago:

- First Tevatron combination for SM Higgs 95% C.L.:
  $\Rightarrow$ 2006 analyses, 0.3–1 fb^{-1}
  (CDF 8384 & D0 5227 Notes)
- 95% exclusion sensitivity $\mathcal{O}(10)\times$SM
- *would need 100 fb^{-1} to reach 2σ sensitivity!*

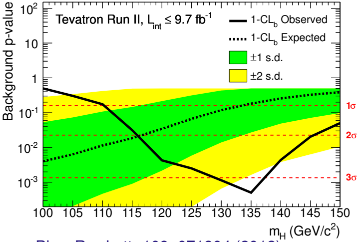
The July 2012 discovery of a new particle compatible with SM Higgs ($m_H \approx 125$ GeV/c^2):

ATLAS, CMS observation in 4ℓ, $\gamma\gamma$ final states:



Phys. Lett. B 716 (2012) 1 and 30

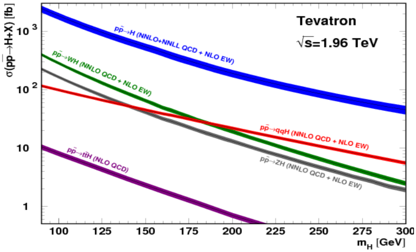
Tevatron evidence in $b\bar{b}$ final state:



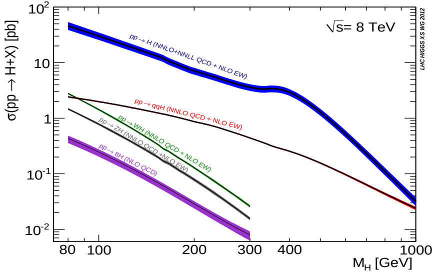
Phys.Rev.Lett. 109, 071804 (2012)

Higgs Production Mode Differences at Tevatron and LHC

Tevatron Higgs production modes (1.96 TeV):

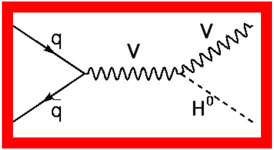


LHC Higgs production modes (8 TeV):



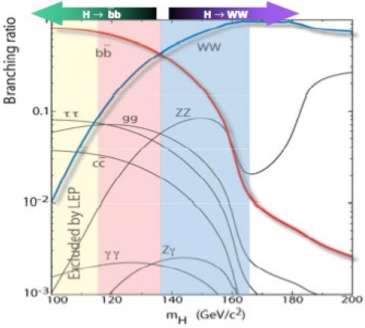
Higgs production rate at LHC much higher than at Tevatron:

- LHC gluon fusion $\times$ 20, Vector Boson Fusion (VBF) $\times$ 30
  - $\Rightarrow$ Abundant production modes for analysis of clean final states with small BR ($\gamma\gamma$, ZZ, WW, $\tau\tau$)
- LHC *VH* associate production $\times$ 4, also higher background:
  - $\Rightarrow$ *Relevant and complementary studies from Tevatron!*



Analysis Channels

SM Higgs decay branching fractions:



Low Mass:

- High BR final states for $m_H \lesssim 135$ GeV/c^2
- Main channel: $qq \rightarrow VH \rightarrow b\bar{b}$
- V to leptons used for online selection and background reduction

High Mass:

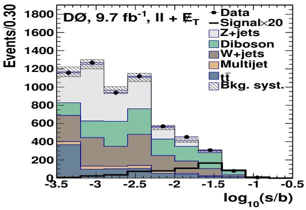
- High BR final states for $m_H \gtrsim 135$ GeV/c^2
- Main channel: $gg \rightarrow H \rightarrow WW$

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$:

- large production rate, small backgrounds but low invariant mass resolution
- Extensive use of MVA: *e.g.* lepton kinematic correlation in EWK $WW \rightarrow \ell\nu\ell\nu$ vs Higgs production

⇒ **In 2008:** first post LEP analysis to exclude presence SM Higgs boson for $M_H \approx 160$ GeV/c^2

Example of D0 $H \rightarrow WW$ BDT output:

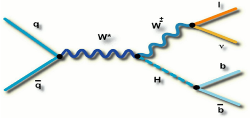


Low Mass Higgs Analyses

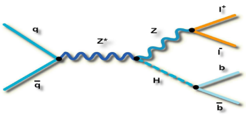
$VH \to b\bar{b}$ is the most sensitive channel at Tevatron:

3 analyses with similar topology: leptons (charged or neutral) + heavy flavor jets

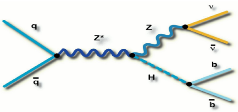
$p\bar{p} \to WH \to \ell\nu + b\bar{b}$



$p\bar{p} \to ZH \to \ell\ell + b\bar{b}$



$p\bar{p} \to VH \to \nu\nu(\nu\not\ell) + b\bar{b}$

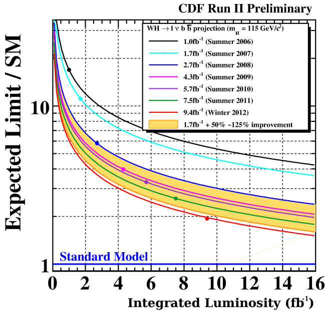


Goal: identify Higgs $M_{b\bar{b}}$ resonance over falling background

- Similar background sources (multi-jet, top, $V + jets$), different relative fractions
- Overcome statistically limited dataset with thorough analysis optimization:

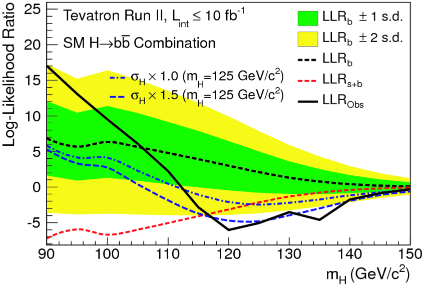
  multiple triggers strategy, extended lepton-ID, b-tag sub-categorization, MVA background rejection and signal discriminant, etc.

Single channel sensitivity improvements w.r.t. 1 fb^{-1} analysis: $>$ 200% over luminosity!

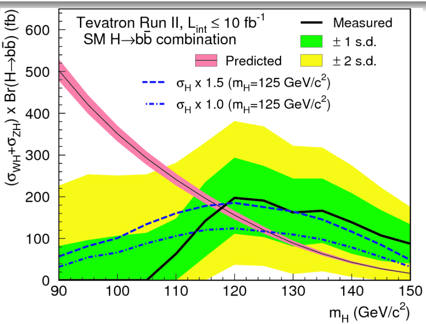


$H \to b\bar{b}$ Results

- Phys.Rev.Lett. 109, 071804 (2012): $H \to b\bar{b}$ low mass *VH* Tevatron combination in 2012
- Phys.Rev.D 88, 052014 (2013): $H \to b\bar{b}$ results from combination of all channels, plus partial re-analysis



SM Higgs 95% exclusion limits



Cross section × BR measurement

Significant excess over background only hypothesis:

- Analysis using both Log Likelihood Ratio (LLR) and Bayesian posterior cross section measurement
- $\sigma(WH + ZH) \times BR(H \to b\bar{b}) = 0.19 \pm 0.09$ pb (SM exp. 0.12 ± 0.01)

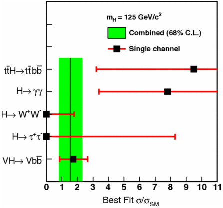
$\Rightarrow$ *Measurement of $H \to b\bar{b}$ competitive with LHC*

Tevatron Combination for All Analysis Channels

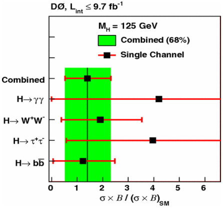
Next step ⇒ investigate SM Higgs properties from combination of all analysis channels > 100!

- SM Higgs hypothesis testing is possible only looking at all the predicted decay modes
- $H \to WW$ and $H \to b\bar{b}$ are the most important, but also $H \to \gamma\gamma$, $H \to \tau\tau$
- Higgs Tevatron studies and results from Summer 2013: Phys.Rev.D 88, 052014 (2013)

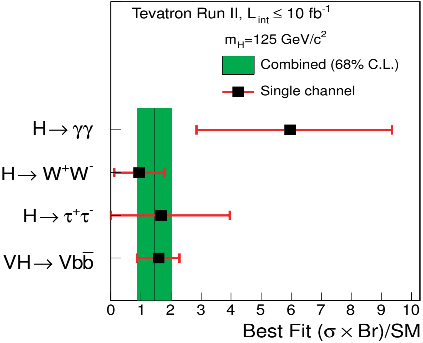
CDF:
PRD 88, 052013 (2013)



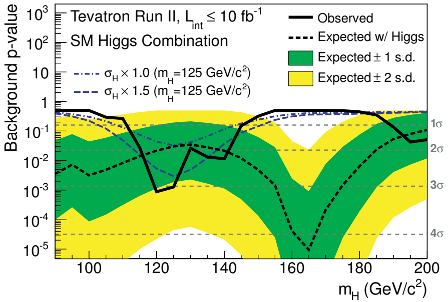
D0:
PRD 88, 052011 (2013)

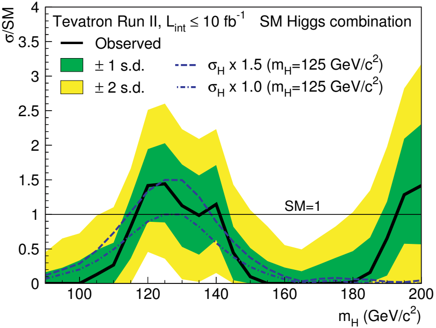


➔



p − values and Cross Section





- Analysis of each channel discriminant with combined likelihood
- minimum p-value 3.1σ (local) at $m_H = 120$ GeV/c^2 (2.0 expected)
- p-value 3.0σ (local) at $m_H = 125$ GeV/c^2 (1.9 expected)
- Maximum likelihood fit with Higgs cross section as free parameter:

$$\mu = \sigma_{obs}/\sigma_{SM} = 1.40 \pm 0.6 \text{ at } m_H = 125 \text{ GeV}/c^2$$

- Consistent cross section between channels and with SM expectation

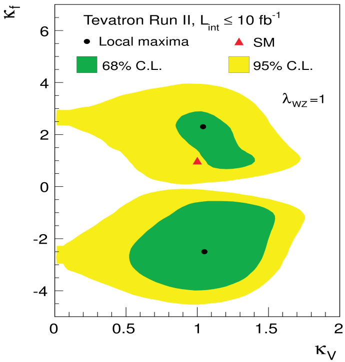
Higgs Coupling Measurements

Extract coupling deviations from SM prediction using per-channel signal rates:

- *Assumptions:*
  $m_H = 125$ GeV/c^2, CP 0^+, negligible width, no invisible decay, preserve unitarity in BR
- LHCHXSWG framework (arxiv:1209.0040)

- κ_f fermion couplings scale
- κ_V boson coupling scale (if $\kappa_Z \equiv \kappa_W$)
- Examples:
  - $\rightarrow$ $\Gamma_{b\bar{b}}, \Gamma_{\tau\bar{\tau}}, \Gamma_{t\bar{t}} \propto \kappa_f^2$
  - $\rightarrow$ $\Gamma_{ZZ} \propto \kappa_V^2$
  - $\rightarrow$ $\Gamma_{WW} \propto R\kappa_V^2$ (with $R = \kappa_W/\kappa_Z$)
  - $\rightarrow$ $\Gamma_{\gamma\gamma} \propto (1.28\kappa_V - 0.28\kappa_f)^2$
- Study of coupling multiplicative parameters with 1-dim and 2-dim (*shown*) Bayesian posteriors
- Most sensitive Higgs production and decay modes via *W*, *Z*, *b*-quark

κ_f vs κ_V (if $\kappa_W = \kappa_Z$)

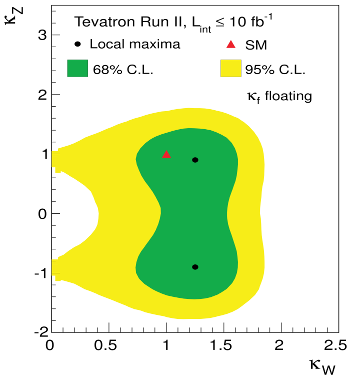


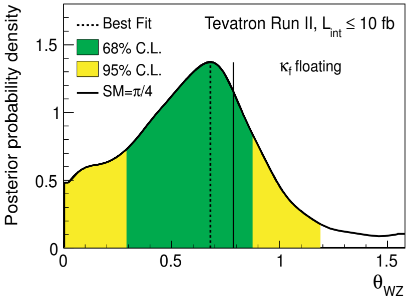
Vector Boson Couplings: κ_W vs κ_Z

Separate measurement of κ_Z vs κ_W

- κ_f is marginalized
- 95% C.L. exclusion of no-Higgs hypothesis: $(\kappa_Z, \kappa_W) = (0, 0)$
- 2-dim best fit:

  $\Rightarrow (\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$





Test of $SU(2)$ custodial symmetry:

- by measuring $\lambda_{WZ} = \kappa_W / \kappa_Z$
- $\theta_{WZ} = \tan^{-1}(\kappa_Z / \kappa_W) = \tan^{-1}(1/\lambda_{WZ})$
- $\theta_{WZ} = 0.68^{+0.21}_{-0.41} \Rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$

Spin and Parity with $VH \to b\bar{b}$

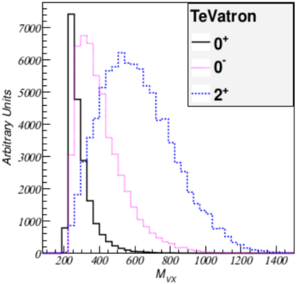
VH production depends on J^P assignment:

- Kinematic differences from behaviors at production threshold

$$cf.Ellis, etal., JHEP1211, 134(2012); Miller, etal., PLB505, 149, (2001)$$

Testing against BSM Higgs models with exotic spin/CP:

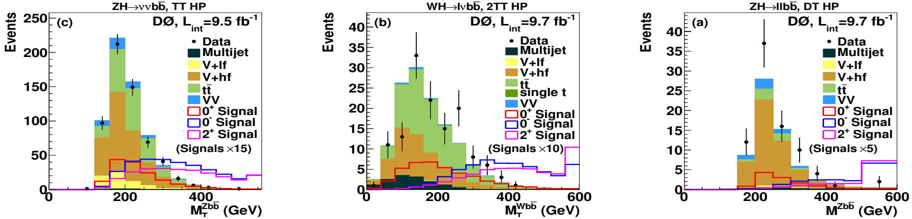
- Given $\beta = 2p/\sqrt{s}$
- 0^+ (SM): S-wave production, $\sigma \propto \beta$ near threshold
- 0^-: P-wave production, $\sigma \propto \beta^3$ near threshold
  $\Rightarrow$ 5-Dim effective-coupling model
- 2^+: D-wave dominates for graviton-like coupling, $\sigma \propto \beta^5$
  $\Rightarrow$ using standard RS graviton model



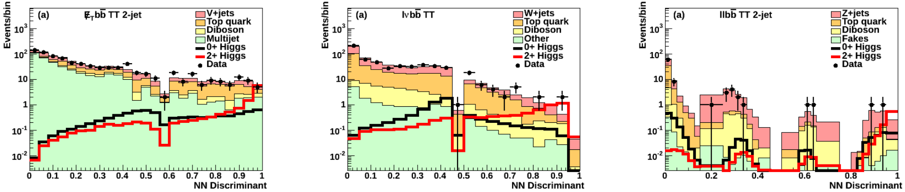
- Probe Higgs J^P with *VH* total mass variables $\Rightarrow$ background discrimination better than for 0^+
- Known m_H used in analysis optimization, possible to re-use Tevatron published results:
  $\Rightarrow$ Same $VH \to b\bar{b}$ datasets and event selection, similar analysis methodologies

CDF and D0 Analyses

D0 Result: discrimination based on total invariant (or transverse) mass, sample split in high/low purity regions to enhance sensitivity [Phys. Rev. Lett. 113, 161802 (2014)]



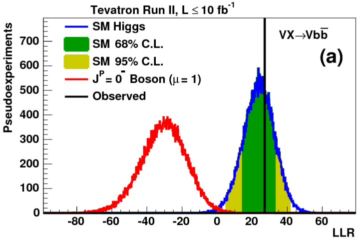
CDF Result: discrimination based on NNs trained against BSM Higgs models [Phys. Rev. Lett. 114, 141802 (2015)]

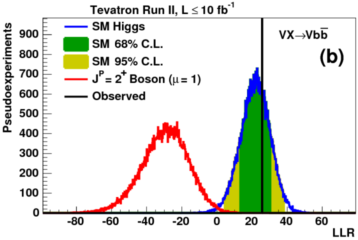


Tevatron Combined Spin and Parity Analysis

Recent result, from April 2015: Phys. Rev. Lett. 114, 151802 (2015)

- LLR test statistics used to distinguish two hypothesis: background plus 0^- or 2^+ Higgs signal (H1) *against* background plus 0^+ Higgs signal (H0)





Very good sensitivity, but model dependent assumptions:

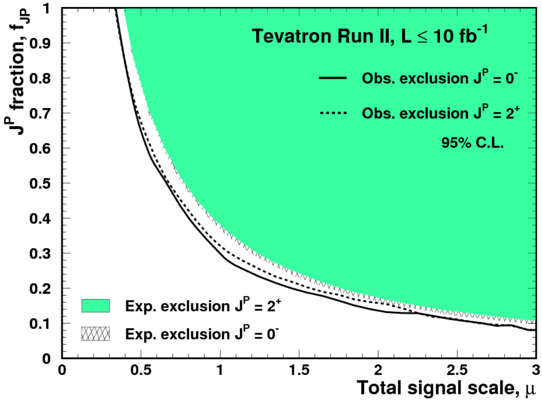
- Exclusions results assuming exotic-Higgs production rates equal to SM Higgs ones:

  $\Rightarrow$ 0^- model excluded at 5.0σ (4.8σ exp)
  $\Rightarrow$ 2^+ model excluded at 4.9σ (4.6σ exp)

Spin/CP Models for Generic Production Rates

Analysis of admixtures of SM Higgs exotic $J^P = 0^-$ (or $J^P = 2^+$) particles:

- fraction of exotic boson production: $f_{J^P} = \mu_{exotic} / (\mu_{SM} + \mu_{exotic})$
- analyzed with respect to total production: $\mu = \mu_{SM} + \mu_{exotic}$



Conclusions and Summary

Tevatron analyses provide good sensitivity to $H \rightarrow b\bar{b}$ final state

Higgs properties studies are often complementary to LHC

Summary of Tevatron Run II Higgs studies:

- Variety of Higgs analysis channels based on full dataset completed and published
- Tevatron data show a consistent picture of the SM Higgs:

  $\Rightarrow$ p-value 3.0σ (local) at $m_H = 125$ GeV/c^2

  $\Rightarrow \mu = \sigma_{obs}/\sigma_{SM} = 1.4 \pm 0.6$ at $m_H = 125$ GeV/c^2
- Coupling strengths of the Higgs boson to W, Z and fermions have been measured to be consistent with the SM expectations

Re-analysis of Tevatron $VH \rightarrow b\bar{b}$ dataset resulted in tight constraints on exotic Spin/CP models:

- $J^P = 2^+, 0^-$ models rejected at $\approx 5\sigma$ C.L. in case of SM-like production rates
- The presence of J^P exotic Higgs admixtures have been also investigated and excluded in a large region of the parameter space

Thanks for Your Attention

Back Up Slides

All Channels and Analysis Details References

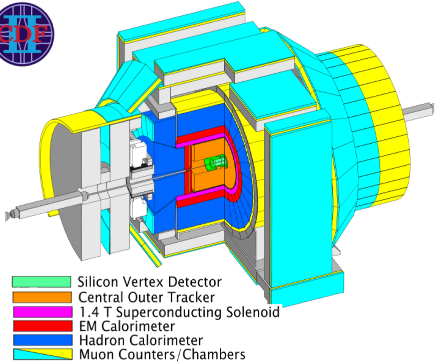
- www-cdf.fnal.gov/physics/new/hdg/Results.html
- www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
- tevnphwg.fnal.gov/results/SM_Higgs_Summer_13

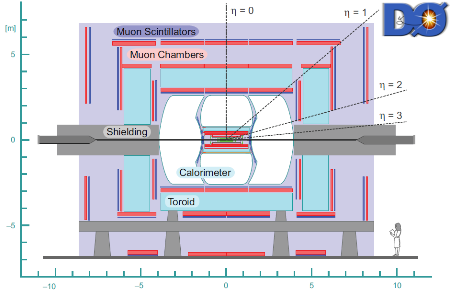
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4 × (5b-tag categories)		9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3 × (2b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2 × (4b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2 × (4b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$ (2b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets, 5 jets, ≥ 6 jets) × (5b-tag categories)		9.45	100–150
$H \to W^+W^-$ 2 × (0 jets) + 2 × (1 jet) + 1 × (≥ 2 jets) + 1 × (low-$m_{\ell\ell}$)		9.7	110–200
$H \to W^+W^-$ (e-τ_{had}) + (μ-τ_{had})		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons) + (trileptons)	$H \to W^+W^-$	9.7	110–200
$WH \to WW^+W^-$ (trileptons with 1τ_{had})		9.7	130–200
$ZH \to ZW^+W^-$ (trileptons with 1 jet, ≥ 2 jets)		9.7	110–200
$H \to \tau^+\tau^-$ (1 jet) + (≥ 2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$ 1 × (0 jet) + 1 × (≥ 1 jet) + 3 × (all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ (4 b-tag categories)×(2 jets, 3 jets)		9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)	$H \to b\bar{b}$	9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$ (2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ (0 jets,1 jet,≥2 jets)		9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{had}\nu$		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ (2 b-tag categories)×(2 jets, 3 jets)	$H \to W^+W^-$	9.7	100–200
$VH \to e^\pm\mu^\pm + X$		9.7	100–200
$VH \to \ell\ell\ell + X$		9.7	100–200
$VH \to \ell\bar{\nu}jjjj$ (≥4 jets)		9.7	100-200
$VH \to \tau_{had}\tau_{had}\mu + X$	$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{had}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

The CDF and D0 Experiments

Multipurpose detectors:



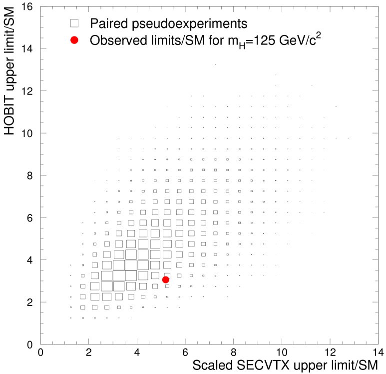


CDF		D0
Silicon ($|\eta| < 2.5$, $r \simeq 20$ cm)	**Inner Tracker**	Silicon ($|\eta| < 3.0$, $r \simeq 10$ cm)
Drift cell ($|\eta| < 1.1$, $r \simeq 130$ cm)	**Outer Tracker**	Fiber ($|\eta| < 1.7$, $r \simeq 50$ cm)
Pb/Fe/Scintillators ($|\eta| < 3.6$)	**Calorimeters**	LAr/U ($|\eta| < 4.0$)
Drift/Scintillators ($|\eta| < 1.5$)	**Muon Chambers**	Drift/Scintillators $|\eta| < 2.0$

CDF $ZH \rightarrow \nu\nu + HF$ Update

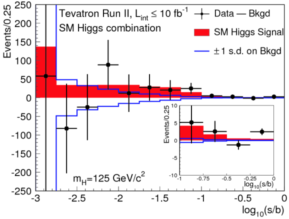
- 2012 result documented in Phys. Rev. Lett. 109, 111805 (2012), Updated 2013 result documented in Phys.Rev.D 87, 052008 (2013)
- Different b-tagging and, therefore, different signal region categorization: new result more sensitive but with lower observed limit
- Fluctuation possible with 7% probability tested with P.E.

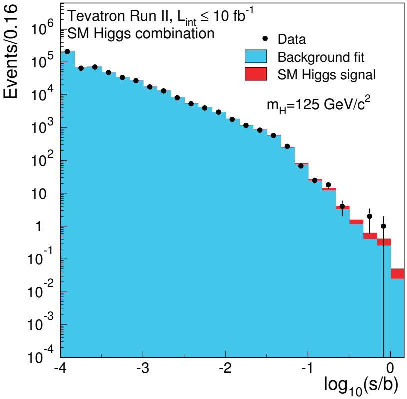
Two-sided p-value by calculating the conditional probability of obtaining a HOBIT result that is as or more discrepant than what we observe, given the S-J reanalysis observed limit



S/B

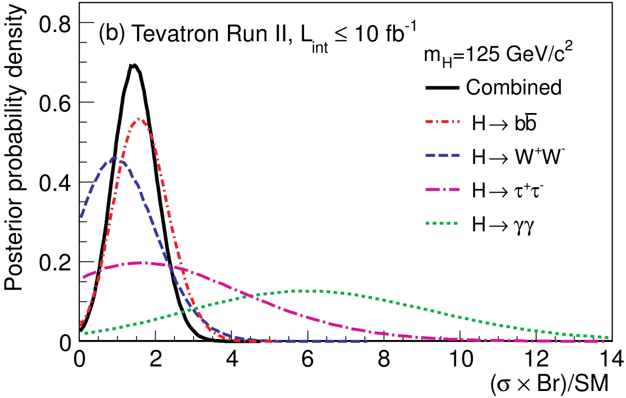
- Classification of all final discriminants in s/b bins
- Preserve importance of each data event
- $\log_{10}(s/b)$ shows agreement over 5 orders of magnitude



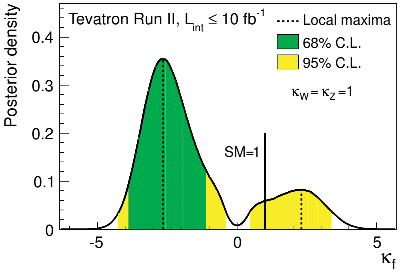


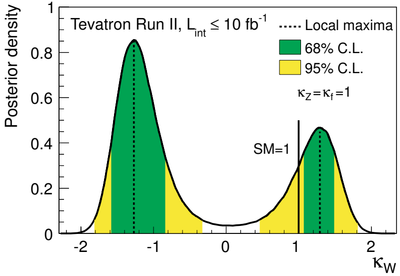
SM Higgs Compatibility Between Final States

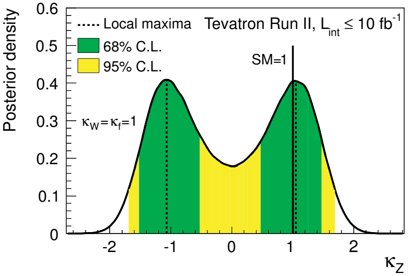
$(\sigma_H \times BR)/SM$ in different final states:



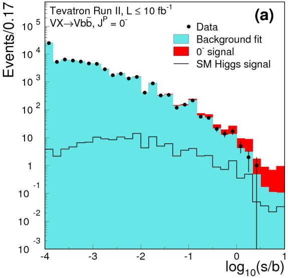
1-Dim κ_f, κ_W, and κ_Z

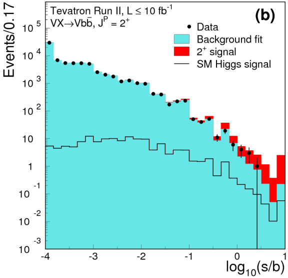


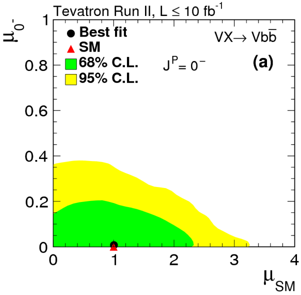


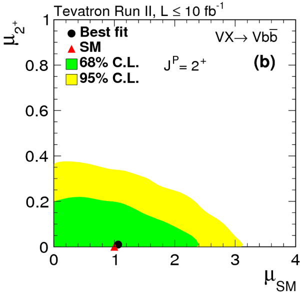


Spin Exclusions Using Measured Higgs Signal Strenght





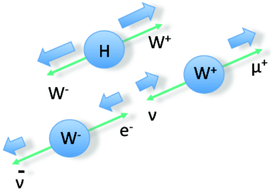




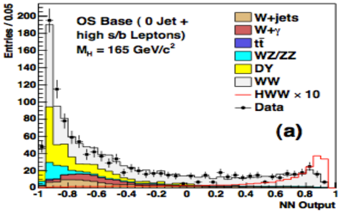
Overview of $H \to WW$ Analyses

- Lepton plus $\not\!\!E_T$ selection (also hadronic τ):
  $\Rightarrow$ s/b event categorization to enhance sensitivity
- Low Higgs mass resolution because of 2ν
- Lepton kinematic correlation for MVA discriminants:
  - $\Rightarrow$ Boosted Decision Trees (BDT), *usually* for D0
  - $\Rightarrow$ Neural Networks (NN), *usually* for CDF

Different di-lepton kinematic of $H \to WW$ decay and WW EWK production (background):

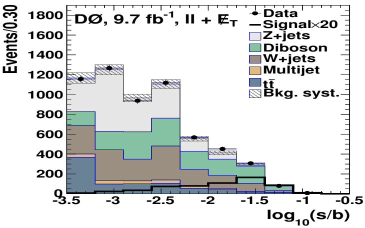


$H \to WW$ NN output:



Phys.Rev. D 88, 052012 (2013)

$H \to WW$ BDT output:



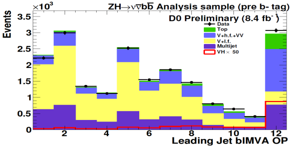
Phys.Rev. D. 88, 052006 (2013)

Low Mass Searches Highlights

- Inclusive trigger strategy: single lepton, only $\not{E}_T$, multiple objects ($\not{E}_T$+jets)
- Improved $\ell/\not{E}_T$ offline ID: relaxed cuts increases MJ $\Rightarrow$ improve lepton ID/MJ-rejection
- b-tag: reduce background to $1/100$ but limits jet selection efficiency ($\simeq$ 50%)
- Final Discriminant: large irreducible backgrounds $\Rightarrow$ MVA sensitivity increase by 10-20%

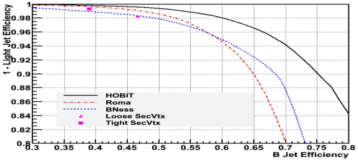
- MVA b-tagging for both D0 and CDF
- Tunable efficiency/contamination working point
- Maximize significance from s/b categorization of signal region

D0 NN b-tagger output composition:



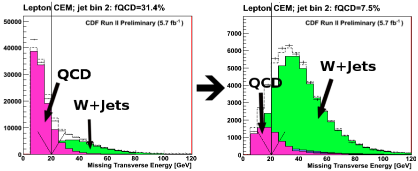
V. M. Abazov et al., Nucl.Instrum.Methods Phys.Res., Sect. A 620, 490 (2010)

CDF b-tag working point comparison:



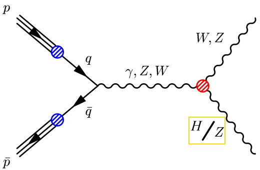
J. Freeman et al., Nucl.Instrum.Methods Phys.Res., Sect. A 697, 64 (2013)

Variety of MJ-rejection techniques (here cut on SVM):



CDF: Phys.Rev.Lett. 109, 111804 (2012), CDF: Phys.Rev.Lett. 109, 111803 (2012), CDF: Phys.Rev.D 87, 052008 (2013)

Analysis Validation with $VZ \to HF$



- Important analysis validation using known SM process as signal
- VZ associate production in $s-$channel with $Z \to b\bar{b}$ mimics $VH \to b\bar{b}$ signature
- $\sigma_{VZ} \times BR(Z \to HF)$ about 6 times VH ($M_H = 125$)
- Higher background due to $W+$jets M_{jj} spectrum

$\Rightarrow$ very small s/b and challenging measurement!

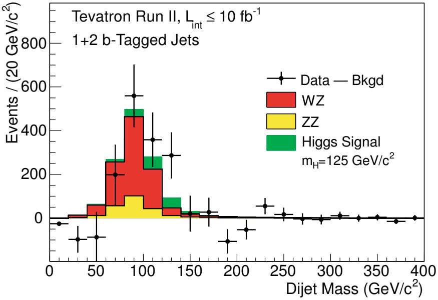
$WZ \to HF$ evidence

- CDF and D0 low mass analyses combined looking at $VZ \to HF$ signal
- Same data-set, analysis techniques, MVA discriminant strategy

$\Rightarrow$ $\sigma_{VZ} = 3.0 \pm 0.6(stat) \pm 0.7(syst)$ pb

$\Rightarrow$ Strong signal evidence at 4.6 σ

$\Rightarrow$ Consistent with $\sigma_{VZ}^{SM,NLO} = 4.4 \pm 0.3$ pb



Background subtracted di-jet invariant mass