Tevatron measurements on Standad Model Higgs

49^{th} Rencontres de Moriond
Electroweak Interactions and Unified Theories

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on behalf of the CDF and D0 Collaborations

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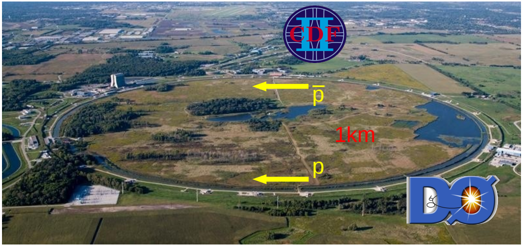
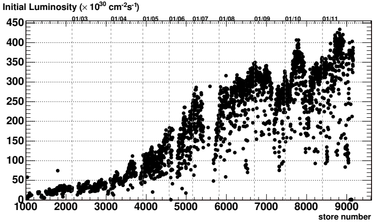
The Tevatron

Presented analyses use full Run II dataset:

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





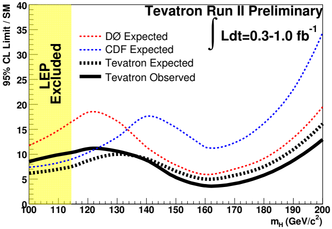
Store initial luminosity $\times 20$ increase over years

$\Rightarrow$ driven by abundance of anti-protons

Tevatron facts:

- Two instrumented collision points: **CDF & D0** experiments
- First superconducting accelerator and largest *anti-matter* source in the world
- 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, 0.3 – 1 fb $^{-1}$ (CDF 8384 & D0 5227 Notes)
- 95% exclusion sensitivity $\mathcal{O}(10)\times$SM
- 100 fb^{-1} *needed to reach* 2σ *sensitivity!*

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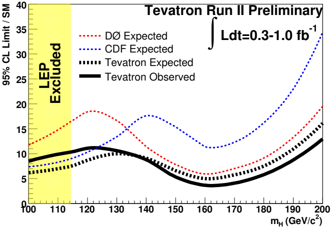

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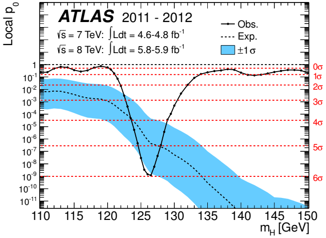
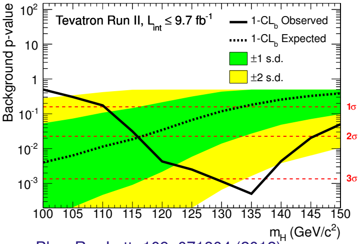
The July 2012 discovery of a new particle compatible with SM Higgs ($m_H \approx 125$ GeV/c^2):

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



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

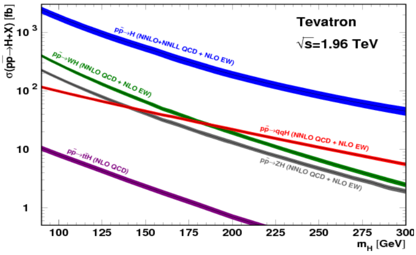
Tevatron evidence in $b\bar{b}$ final state:



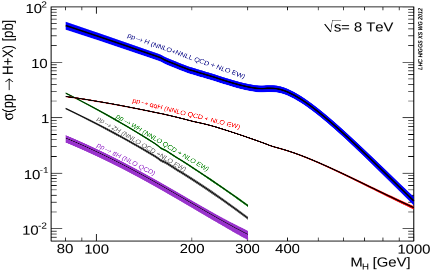
Phys.Rev.Lett. 109, 071804 (2012)

Higgs Production Mode Differences at Tevatron and LHC

Tevatron Higgs production modes (1.96 TeV):

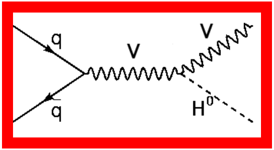


LHC Higgs production modes (8 TeV):



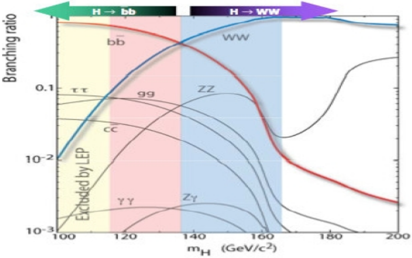
Higgs production rate at LHC much higher than at Tevatron:

- 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 Classification

SM Higgs decay branching fractions:



High Mass:

- High BR final states for $m_H \gtrsim 135$ GeV/c^2
- Main channel: $gg \rightarrow H \rightarrow WW$
- $WW \rightarrow \ell\nu\ell\nu$: low background
- High Higgs production rate

Low Mass:

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

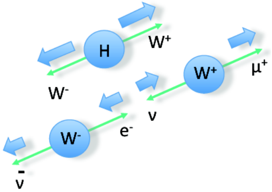
Peculiarity of $m_H = 125$ GeV/c^2: $BR(H \rightarrow b\bar{b}) \simeq 0.58$, $BR(H \rightarrow WW) \simeq 0.21$

$\Rightarrow$ Both low and high mass analyses contribute to properties study

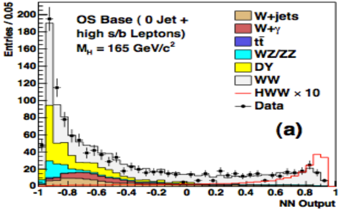
Overview of $H \rightarrow WW$ Analysis

- 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 $H \rightarrow WW$ decay and WW EWK production (background):

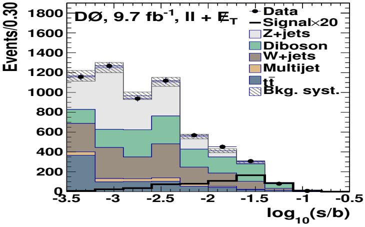


Example of CDF $H \rightarrow WW$ NN output:



Phys.Rev. D 88, 052012 (2013)

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



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

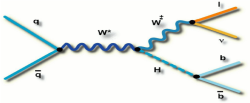
2008: first post LEP analysis to exclude presence SM Higgs boson in mass range

Overview of Low Mass Higgs Analyses

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

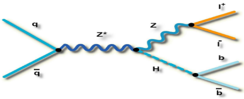
3 analyses with similar topology: leptons (charged or neutral) + heavy flavor jets

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



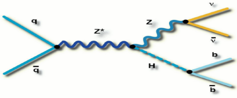
CDF: Phys.Rev.Lett. 109, 111804 (2012),
D0: Phys.Rev.Lett. 109, 121804 (2012),
Phys.Rev.D. 88, 052008 (2013)

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



CDF: Phys.Rev.Lett. 109, 111803 (2012),
D0: Phys. Rev. Lett. 109, 121803 (2012),
Phys.Rev.D. 88, 052010 (2013)

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



CDF: Phys.Rev.D 87, 052008 (2013),
D0: Phys.Lett.B 716, 285 (2012)

- Similar background sources, different relative fractions between final states
- Aim to identify Higgs $M_{b\bar{b}}$ resonance over falling background
- Background estimate with mixture of MC/data driven extraction from Control Regions (CR)

Backgrounds	*Shape*	*Normalization*
WW,WZ,ZZ, $t\bar{t}$, single-top	MC based	NLO,NNLO (Theory)
Multi-Jet (MJ)	Data driven	Fit to data
W/Z+light flavor	MC (ALPGEN), CR weighted	data CR
W/Z+heavy flavor	MC based (ALPGEN)	LO, fit to data

Statistically limited dataset ⇒ Relax cuts ⇒ Keep background under control ⇒ **Iterate**

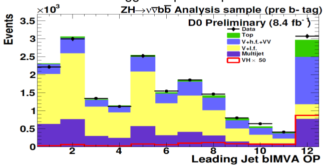
Low Mass Searches Optimization

Every aspect of analyses thoroughly optimized (often using MVA):

- 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 ⇒ improve lepton ID/MJ-rejection
- b-tag: reduce background to $1/100$ but limits jet selection efficiency ($\simeq$ 50%)
- Final Discriminant: large irreducible backgrounds ⇒ MVA sensitivity increase by 10-20%

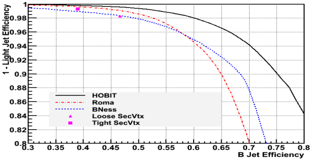
- MVA b-tagging for both D0 and CDF
- Tunable efficiency/contamination working point
- Maximize significance from s/b categorization of signal region

D0 NN b-tagger output composition:



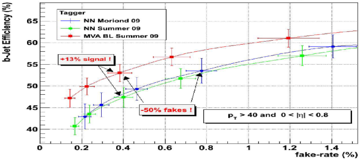
V. M. Abazov et al., Nucl.Instrum.Methods Phys.Res., Sect. A 620, 490 (2010)

CDF b-tag working point comparison:



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

D0 b-tag algorithm improvements and working points:



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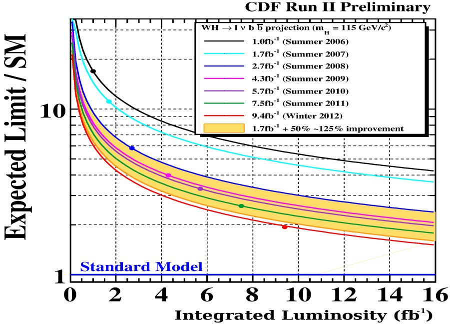
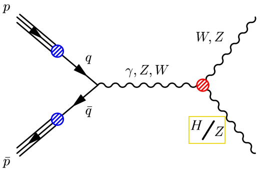


Single channel sensitivity improvements w.r.t. 1 fb^{-1} analysis was also $>$ 200% (over luminosity)!

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!

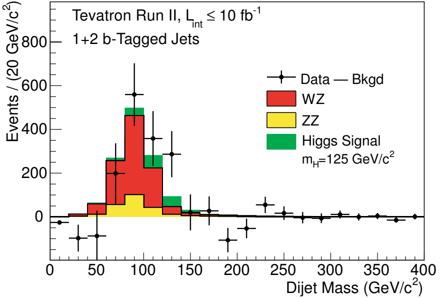
$WZ \to HF$ evidence

- 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 $4.6\ \sigma$

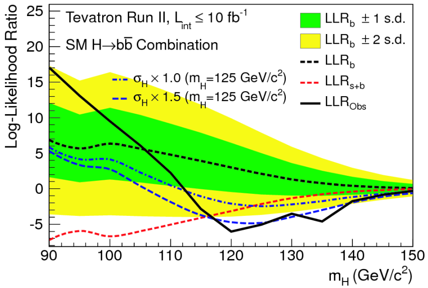
$\Rightarrow$ Consistent with $\sigma_{VZ}^{SM,NLO} = 4.4 \pm 0.3$ pb



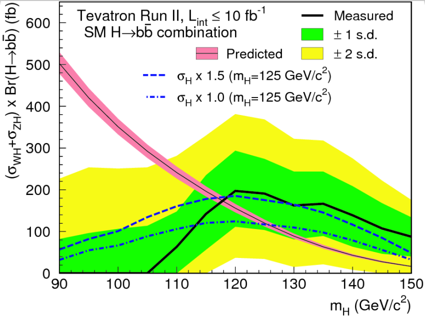
Background subtracted di-jet invariant mass

$H \to b\bar{b}$ 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): properties of $H \to b\bar{b}$ from all channel update in **July 2013**



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*

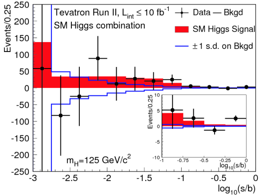
Tevatron Combination for All Analysis Channels

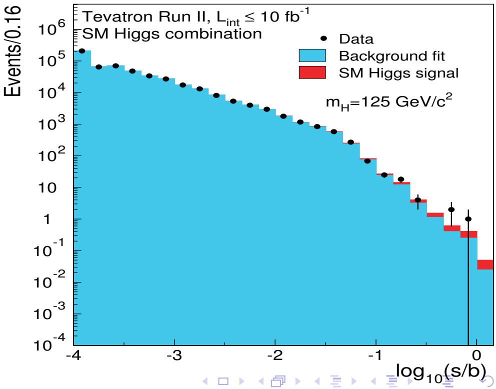
Next step ⇒ analyze SM Higgs from combination of all analysis channels, > 100!

- $H \to WW$ and $H \to b\bar{b}$ are the most important, but also $H \to \gamma\gamma$, $H \to \tau\tau$
- SM Higgs hypothesis testing is possible only looking at all the predicted decay modes
- Measure parameter of new particle: Summer 2013 Results

The global picture:

- 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

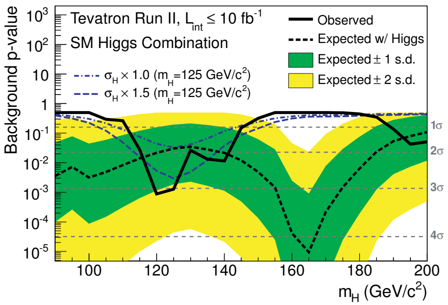


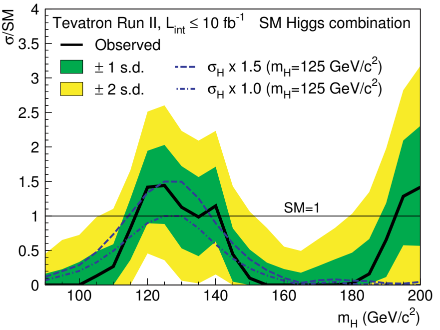


p – values and Cross Section

The full Tevatron combination results:

- Analysis of each channel discriminant with combined likelihood
- p-value 3.0σ (local) at $m_H = 125$ GeV/c^2 (1.9 expected)
- $\mu = \sigma_{obs}/\sigma_{SM} = 1.44^{+0.59}_{-0.56}$ at $m_H = 125$ GeV/c^2
- Consistent cross section between channels and with SM expectation



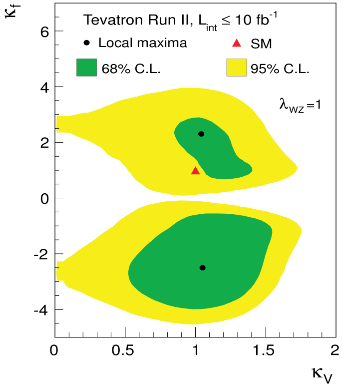


Higgs Coupling Measurements

- Most sensitive Higgs production and decay modes via W, Z, b-quark
- Extract coupling deviations from SM prediction from per-channel signal rates
- *Assumptions:* $m_H = 125$ GeV/c^2, *negligible width, CP* 0^+, *no invisible decay*

κ_f vs κ_V (if $\kappa_W = \kappa_Z$)

- κ_f fermion couplings scale
- κ_V boson coupling scale (if $\kappa_Z \equiv \kappa_W$)
- Examples:
  - $\rightarrow$ $\Gamma_{b\bar{b}} \propto \kappa_f^2$, $\Gamma_{\tau\bar{\tau}} \propto \kappa_f^2$, $\Gamma_{ZZ} \propto \kappa_V^2$
  - $\rightarrow$ $\Gamma_{WW} \propto R\kappa_V^2$ (with $R = \kappa_W/\kappa_Z$)
- Preserve unitary in BR:
  es. $\Gamma_{\gamma\gamma} \propto (1.28\kappa_f - 0.28\kappa_V)^2$
- Study of coupling multiplicative parameters with 1-dim and 2-dim (*shown*) Bayesian posteriors

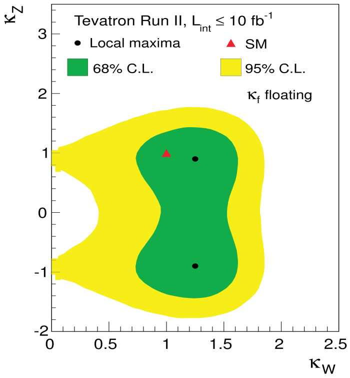


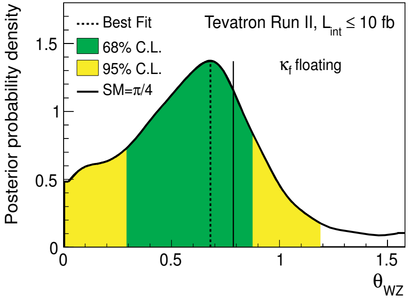
Vector Boson Couplings: κ_W vs κ_Z

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

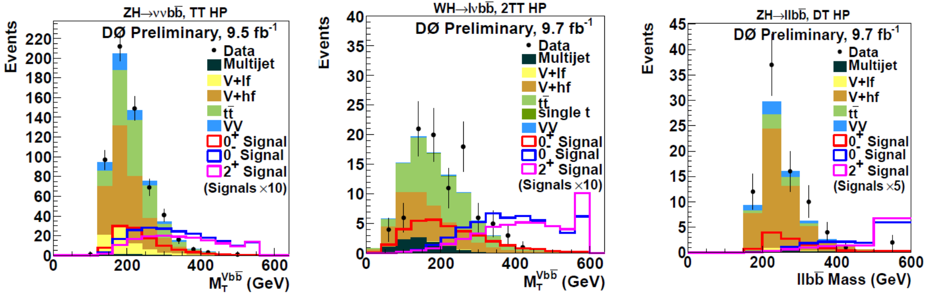
Additional Properties: Spin and Parity

- *VH* production processes differ depending on J^P assignment
- Kinematic differences from behaviors at production threshold, if $\beta = 2p/\sqrt{s}$:

- 0^+: S-wave production, $\sigma \propto \beta$ near threshold
- 0^-: P-wave production, $\sigma \propto \beta^3$ near threshold
- 2^+: D-wave dominates for graviton-like coupling, $\sigma \propto \beta^5$

cf. Ellis, et al., JHEP 1211, 134 (2012), and Miller, et al., PLB 505, 149, (2001)

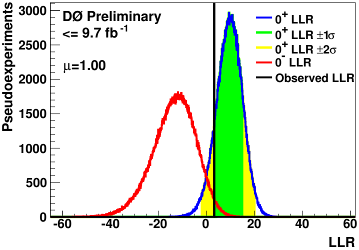
Probe Higgs J^P with *VH* total mass variables ⇒ background discrimination better than for 0^+:

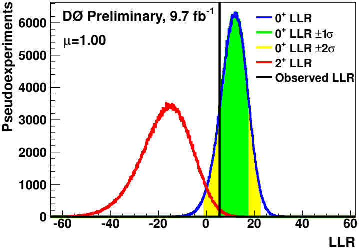


- 2^+ result Summer 2013: D0 Note 6387
- 0^- recent result (Autumn 2013): D0 Note 6406

Results of Spin and Parity Analysis

- Known m_H used in analysis optimization:
  - $\Rightarrow$ selection of High/Low purity regions in reconstructed mass
- LLR test statistics used to distinguish two hypothesis with CL_s:
  - $\Rightarrow$ H1 (Test): background plus 0^- or 2^+ Higgs signal
  - $\Rightarrow$ H0 (Null): background plus 0^+ Higgs signal
- Two scenarios: SM like $\sigma_{VH} \times BR(b\bar{b})$ (*shown*), or D0 measured rate ($\mu = 1.23$)



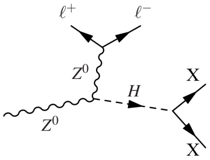


Exclusions results:

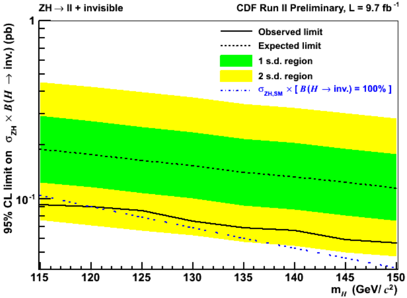
- 0^- model excluded at > 97.9% C.L. (2.3σ obs, 3.1σ exp)
- 2^+ model excluded at > 99.9% C.L. (2.4σ obs, 3.2σ exp)
- Very good sensitivity but model dependent assumptions

Invisible Higgs

- **New** CDF analysis testing exotic Higgs models: CDF Note 11068
- First measurement at the Tevatron probing $\sigma_{ZH} \times BR(H \to \text{invisible})$
- If kinematically accessible, decays to heavy unknown and weakly interacting particles are likely because of Yukawa coupling ($\propto m$) to Higgs
- $ZH \to \ell\ell + \not{E}_T$: $82 < M_{\ell\ell} < 100$ GeV/c^2, clean signature



- Bayesian 95% C.L. exclude 100% $BR(H \to \text{invisible})$ for $m_H < 120$ GeV/c^2



Summary and Prospects

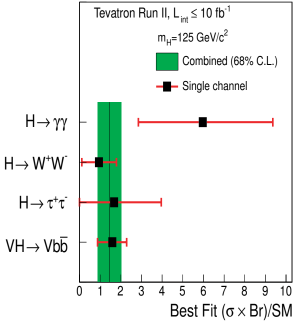
Summary of Tevatron Run II Higgs studies:

- High and low Higgs mass analysis channels based on full dataset completed and published
- Data show a consistent picture of the SM Higgs:
  - $\Rightarrow$ p-value 3.0σ (local) at $m_H = 125$ GeV/c^2
  - $\Rightarrow \mu = \sigma_{obs}/\sigma_{SM} = 1.44^{+0.59}_{0.56}$ at $m_H = 125$ GeV/c^2

Recent results and work in progress:

- $VH \rightarrow b\bar{b}$ datasets re-analyzed by D0 collaboration extracting spin and CP measurements:
  - $\Rightarrow$ $J^P = 0^+$ nature of the new particle are favored
  - $\Rightarrow$ $J^P = 2^+, 0^-$ models rejected at $> 97\%$ C.L.
  - $\Rightarrow$ Tevatron combination is in progress
- Exotic Higgs properties:
  - $\Rightarrow$ new analysis $H \rightarrow$invisible

$(\sigma \times BR)/SM$ for decay channel:



Tevatron analyses still provide good sensitivity to $H \rightarrow b\bar{b}$ final state and Higgs properties studies are often complementary to LHC

Thanks for Your Attention

Back Up Slides

All Channels and Analysis Details References

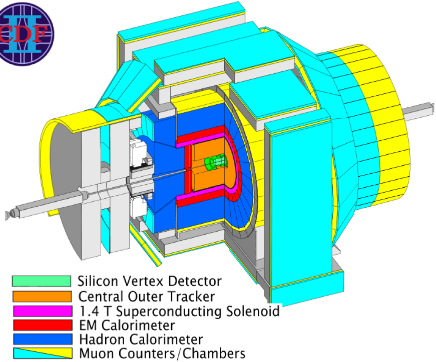
- www-cdf.fnal.gov/physics/new/hdg/Results.html
- www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
- tevnphwg.fnal.gov/results/SM_Higgs_Summer_13

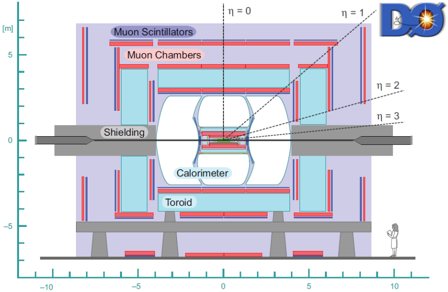
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4 × (5b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3 × (2b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2 × (4b-tag categories)		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-$m_{\ell\ell}$)	$H \to W^+W^-$	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)		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)	$H \to b\bar{b}$	9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)		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)	$H \to W^+W^-$	9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\text{had}}\nu$		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ (2 b-tag categories)×(2 jets, 3 jets)		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
$VH \to \tau_{\text{had}}\tau_{\text{had}}\mu + X$	$H \to \tau^+\tau^-$	8.6	100-150
$H{+}X \to \ell^\pm\tau^\mp_{\text{had}}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

The CDF and D0 Experiments

Multipurpose detectors:

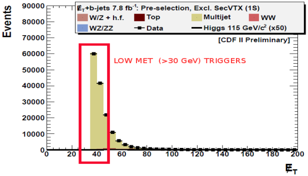




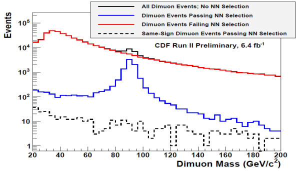
Silicon ($\|\eta\| < 2.5$, $r \simeq 20$ cm) Drift cell ($\|\eta\| < 1.1$, $r \simeq 130$ cm)	**Inner Tracker** **Outer Tracker**	Silicon ($\|\eta\| < 3.0$, $r \simeq 10$ cm) Fiber ($\|\eta\| < 1.7$, $r \simeq 50$ cm)
Pb/Fe/Scintillators ($\|\eta\| < 3.6$)	**Calorimeters**	LAr/U ($\|\eta\| < 4.0$)
Drift/Scintillators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

Analysis Improvement Examples

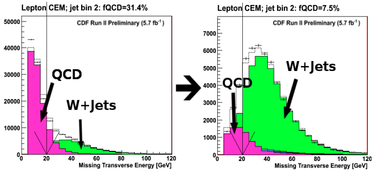
Low trigger thresholds (multi-dim. turn-on model):



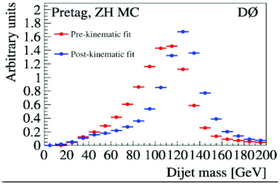
Lepton ID with NN selection:



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



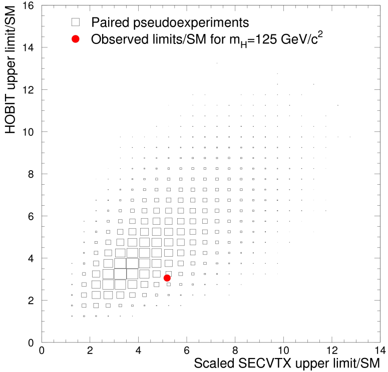
$Z \to \ell\ell$ kinematic fit to improve M_{jj} resolution:



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

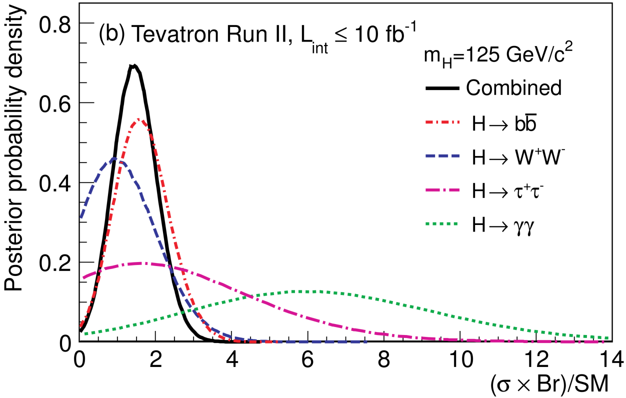
- 2012 result documented in Phys. Rev. Lett. 109, 111805 (2012), Updated 2013 result documented in Phys.Rev.D 87, 052008 (2013)
- Different b-tagging and, therefore, different signal region categorization: new result more sensitive but with lower observed limit
- Fluctuation possible with 7% probability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

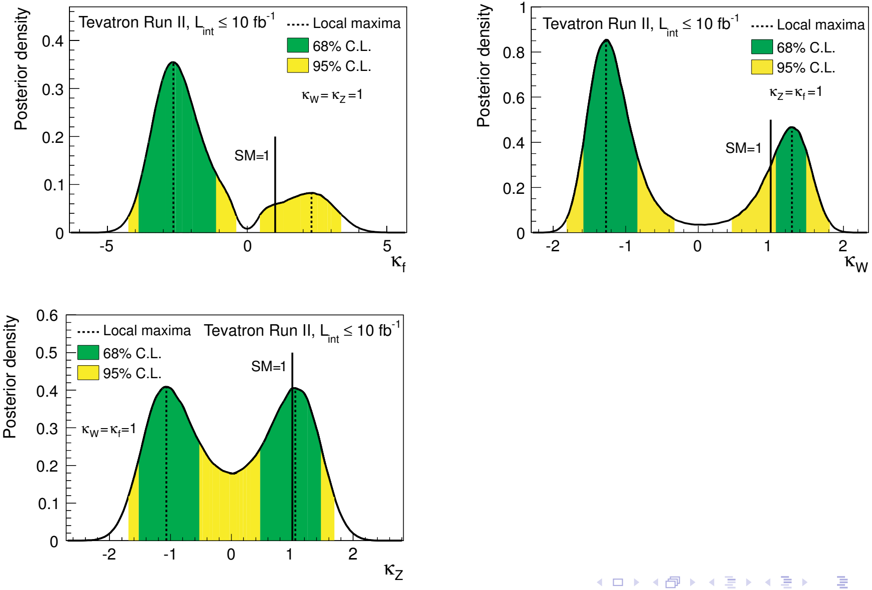


SM Higgs Compatibility Between Final States

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



1-Dim κ_f, κ_W, and κ_Z



Spin Exclusions Using Measured Higgs Signal Strenght