Higgs Boson Physics at CDF

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SLAC Experimental Seminar
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A Higgs-Like Boson Discovered!

- July 4th, simultaneous, independent announcement of discovery by ATLAS and CMS
  - Observed \(~5 \sigma\) significance
  - Produced in gluon and vector boson fusion
  - Decays to pairs of:
    - Photons, W bosons, Z bosons

- Definitely know:
  - Is a boson, not spin 1.
  - Couples (directly) to W and Z

- Reasonable questions:
  - Couplings to fermions? Seems reasonable, but need to see directly
  - Spin and parity?
  - Other new particles within reach?
Overview

- Why we thought it was there
- How we looked
- What we saw
- What we might see soon
Motivation

- Gauge invariance suggests massless W and Z bosons
  - W, Z observed to be massive
- In SM, W&Z observable masses arise via electroweak symmetry breaking
- Ground breaking work on EWSB:
  - F. Englert, R. Brout, _PRL 13 (9): 321–323._
  - P.W. Higgs, _PRL 13 (16): 508–509._
- Proposed mechanism of EWSB predicts an additional observable scalar particle.
  - Observable at the Tevatron?
Experimental Status (June)

- Resulting boson mass is unpredicted by theory
  - Mass determines production and decay rates (next slide)
- Indirect constraints (MW, Mtop) prefer a SM Higgs Boson with MH below 158 GeV
  - CDF&DØ 2012 W mass!
- Pre-Discovery Direct Searches: 95% CL Exclusions of MH in SM:
  - **LEP**: Exclude MH < 114 GeV
    - arXiv:0602042v1
  - **Tevatron**:
    - Exclude MH in [156,177] GeV
    - arXiv:1107.5518
  - **LHC**:
    - Exclude MH <115, or [~127, 600] GeV
    - arXiv:1202.1408 (ATLAS)
    - arXiv:1202.1488 (CMS)
SM Higgs Boson Production in $p\bar{p}$ Collisions

Associated Production

Most Sensitive For $MH < 135$

Direct Production

Most Sensitive for $MH > 135$
Decay Modes of the SM Higgs Boson

- Mostly bottom quarks!
  - QCD $bb > 8$ orders-of-magnitude higher at hadron colliders
  - Photon and lepton backgrounds better controlled
  - $bb$ is a dirty job, but someone has to do it
  - Need most of these decays to be confident it's really a SM Higgs boson!
The Tevatron compared to SLC

FNAL

SLAC

1 km
• **Superconducting storage ring**
  - 1 km radius, 1 beam-pipe
  - Collisions 1985-2011
• **Run II: Mar 2001-Sept 2011**
• **Produced pp collisions at 1.96 TeV**
  - 36x36 bunches
  - ~$E_{10} - E_{11}$ particles per bunch
  - ~21μs per revolution
  - ~1.5 MJ beam energy
    - Compare to ~200 kJ for HER
    - Compare to ~400 MJ for LHC
• **Not like a lepton collider:**
  - Quark, gluon scattering
  - PDFs means $<< 2$ TeV goes into hard scatter
Detectors at The Tevatron

- The Tevatron's collisions were recorded by two general purpose experiments: CDF and DØ
The Collider Detector at Fermilab

- Silicon tracking $|\eta|<2-2.5$
- Drift cell tracker
  1.4 Tesla field, $|\eta|<1.1$
- Calorimeter:
  Pb/Fe+Plastic Scintillator
  $|\eta|<3.2$
- Muon chambers: $|\eta|<1.5$
- Jet Energy Scale Uncertainty (High-ET): 2-3%

~4500 Tons (Central)
~400 Tons (Muon Walls)
~800 Tons (End Toroids)
Candidate Associated Production Events in Data at CDF

ZH\rightarrow\mu\mu bb

ZH\rightarrow ee bb

ZH\rightarrow\mu\mu bb

WH\rightarrow e\nu bb
Data Taking Conditions

- The Tevatron bunch crossing rate was \(~2.5 \text{ MHz}\).
- Full readout saturated at \(~100 \text{ Hz}\).
- Rates at \(L=1\times10^{32} \text{ cm}^{-2}\text{s}^{-1}\):
  - Jets (\(ET>40 \text{ GeV}\)): \(~300 \text{ Hz}\)
  - W: \(~3 \text{ Hz}\)
  - Top Pair: \(~25/\text{hour}\)
  - SM Higgs \(~10/\text{week}\):
- Triggers designed to select events on the fly, with varying degrees of reconstruction
  - keep most signal-like events, discard others
  - Mixture of custom hardware and commodity PCs
Avoid this Background

Prefer These

Data Taking Conditions

Cross section (barns)

Higgs mass (GeV)/c^2

1.0 x 10^10

mb

6 x 10^6

b\bar{b}

μb

4000

W

400

nb

Z

1

t\bar{t}

0.3

pb

single top

1.0 x 10^{-12}

Higgs (ZH + WH)

fb

1.0 x 10^{-16}
Trigger Efficiencies

- Data taking bandwidth budgets dictate MET trigger thresholds be set near or above kinematic peak.
  - Lost signal!
- I'll tell you later how we got some of it back!
The Tevatron RunII Datasets

- Full results presented here
- 11/fb on tape
  - ~10/fb good for analysis
- Typical #vertices/event 1-3
- Candidates in 10/fb:
  - B0s→J/ψφ : ~10K-20K
  - t\bar{t}→e/μ+\geq 1 b-jet : ~2000
  - Z→ee/μμ : ~600K
  - (W→e/μ)+dijet : ~100K
  - >30 GeV photons : ~20M
  - ZZ→4l: ~10
  - t\bar{t}+γ→γ+l+jets: ~50
From Events to Statements About Signal

- Collect data events
  - Reconstruct their properties
  - Select signal-like candidates
  - Select control samples
- Simulate the background and signal components
  - Estimate uncertainties
- Sift events according to signal significance
  - Multivariate discriminants
- Make a statement about compatibility w/ background or s+b hypotheses
Creating Discriminating Variables

- Identify regions of high signal density
- Some analyses, like $\gamma\gamma$, use the “reconstructed Higgs mass”.
- In WH, using $M(jj)$ is about 75% as strong a multivariate method
- Many Options:
  - Scattering matrix element (ME) or dynamic likelihood methods (DLM)
  - CDF often uses kernel machines like Neural/Bayesian/ensemble networks, SVMs
  - DØ often uses boosted decision trees (BDT)
  - Negligible performance difference between MVA methods when thoroughly implemented
    - See CDF WH search with NN and ME in 5.7/fb.
    - Human effort in implementation and intuition tends to govern preferences
Bayesian Searches (CDF)

- Make a statement about belief in Cross section ratio: \( R = \frac{\sigma}{\sigma_{\text{SM}}} \)
- Compute joint-poisson likelihood
  - Compatibility of data with each hypothesis
- Flat prior: \( R = [0, \text{MAX}] \)
- Nuisance parameters:
  - Detector response, background
  - cross sections, PDFs, etc.
- Integrate likelihood over nuisance parameters:
  - Produces posterior probability density as function of \( R \) alone

Prior Probability Density

Posterior

Upper Limit
Exclude: \( < RxSM \)

Begin to Observe?
Bayesian vs. Frequentist

• D0, ATLAS, CMS all use Modified Frequentist limit calculations
  • Bayesian and M.F. Agree numerically to ~1% for searches with large numbers of observed events.

• Technical advantage
  • Bayesian method relies on integrating over nuisance parameters
    – Profile likelihood method relies on a fitting procedure, which involves computing derivatives
  • Integrating is less sensitive to discontinuities in nuisance parameter priors
Bayesian Searches (CDF)

- Perform this analysis for each assumed Higgs Mass:
  - Data (**Observed upper limit**)
  - Simulation: (**Expected sensitivity**)
    - **Construct ensemble of background-only pseudoexperiments**
      - Each pseudoexperiment has same statistical uncertainty as data, selected from one systematic assumption
    - **Shaded bands show typical excursions (for the BG hypothesis)**
Overview of Individual Higgs Searches

- For July 2012 results:
  - SM predicts \( \sim 167 \) Higgs events (125 GeV) reconstructed and selected
  - SM background of \( \sim 200 \)K
- 11 CDF analyses:
  - \( \sim 88 \) orthogonal sub-channels.
- In region 115-127 GeV, WH, ZH, VH, and WW contribute \( \sim 90\% \) of total weight of combination.
Identify 2 leptons, separate by jet multiplicity

- Capitalize on scalar nature of Higgs:
  - Spin correlations
  - Leptons closer in signal than background

- **2012 improvement:**
  - Redefine lepton “isolation”
  - Avoid mutual isolation veto for two nearby leptons.
  - More acceptance!
High-Mass Combined Searches

CDF: 8 sub-channels

- Best s/b: ~1:1 (165 GeV)
- New: Low Mll channel!
Why So Many Categories?

- Three major advantages
  - Sensitivity is roughly proportional to integrated signal/$\sqrt{BG}$
    - Weaker categories dilute stronger ones
  - Individual categories are affected by nuisance parameters in distinct ways
    - Isolating distinct samples can constrain nuisance parameters in situ!
  - **NEW**: different production and decay mode sensitivities in different categories?
    - Fermionic-to-bosonic coupling ratios!
    - See J. Wacker's colloquium talk from Sep 24.
High-Mass Combined Searches

- Low-mass: $W\gamma$
- High Mass: $DY$
- More VBF in 2-jet-category
Associated Production Channels

\[ ZH \rightarrow l^+ l^- b \bar{b} \quad \text{\( W^\pm \rightarrow l^\mp v b \bar{b} \)} \quad \text{\( ZH \rightarrow \nu \nu b \bar{b} \)} \]
Associated Production Channels

$ZH \rightarrow l^+l^-b\bar{b}$

$Wl^\pm \nu b\bar{b}$

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

$Z \rightarrow e^+e^- + \text{jets}$

CDF Run II Preliminary

$\sigma_{Z/\gamma^* (\rightarrow e^+e^-)} + 1 \text{ jet}$

$\sigma_{Z/\gamma^* (\rightarrow e^+e^-)}$ vs $M_{Z_{\text{inv}}}$ [GeV/c$^2$]
Associated Production Channels

\( ZH \rightarrow l^+l^-b\bar{b} \)

\( Wl \rightarrow l^\pm v\bar{b} \)

\( ZH \rightarrow \nu\bar{\nu}b\bar{b} \)

\( W \rightarrow l\nu + \text{jets} \)

\( Z \rightarrow e^+e^- + \text{jets} \)

CDF Run II Preliminary

\( Z/\gamma^*(\rightarrow e^+e^-) + \geq 1 \text{ jet} \)

\( W(\rightarrow e\nu) + \geq 1 \text{ jet} \)

Data 320 pb\(^{-1}\)
Combined
Signal
QCD
EWK+top
Associated Production Channels

\[ ZH \rightarrow l^+ l^- b \bar{b} \]

\[ Wl \rightarrow l^\pm \nu b \bar{b} \]

\[ ZH \rightarrow \nu \nu b \bar{b} \]
More Acceptance, Same Background

- Use multivariate rejection of instrumental bkgds
- Use looser kinematic selections for more pure samples (muons)
More Trigger Acceptance

- Data Driven Multivariate Triggers
  - Use Multiple Triggers in MASSIVE LOGICAL OR
  - MET, Jets, tracks, Jet+MET, Lepton+MET......
    - ZH uses EVERY Lepton/MET trigger
- Method:
  - Select events in orthogonal sets: A, B, C, D...
  - Use NN to regress on p(A|B), p(A|C)....
    - NN output becomes weight
  - Automatically handles collider, detector time variations.
  - Requires negligible personpower

\[\text{ZH} \rightarrow \mu\mu bb\]

\[\text{ZH} \rightarrow \nu\nu bb\]

\[\text{Jet}\]

\[\mu\]

\[\mu\]

\[\text{Jet}\]

\[\text{Jet}\]

\[\text{Jet}\]

\[\text{Jet}\]

\[\text{Jet}\]

\[\text{Missing Energy (MET)}\]
Jet Identification

- Towers clustered with a modified cone algorithm
  - Cone R=0.4
- Calibrated via Z+j, γ+j, dijet balancing
  - Linearity
  - Out-of-cone
  - Underlying event
  - Residual JES uncertainty: ~5%
- Additional resolution improvements
  - CDF: In-situ Z+jj+MET → Z+jj
  - Smearing of Mjj 10-20%

CDF Run I Preliminary (9.45 fb⁻¹)
Identifying b-jets

- The mean lifetime of b-mesons is ~1 ps
- b-hadrons produced in collisions can travel ~mm before decaying
- Jets with secondary decay vertexes, or with single tracks significantly displaced from the beamline are “tagged”
- Charm-meson and mis-reconstructed u,d,s,c,g jets are a background
B-Tagging for Signal Significance

CDF Run II Preliminary 9.45 fb

**Z+Jets before b-tagging**

Signal × 500

LL

Signal × 100

T

Signal × 75

TL

Signal × 25

TT

Signal × 1!
Improved b-Tagging

- 2011: CDF WH (ZH,VH) used 3 (2) different b-taggers in orthogonal series
- 2012: New CDF Neural Network b-tagger
  - Uses most sensitive variables from previous CDF taggers
    - Uses semileptonic b-decay muons, Jet tower Mass, secondary vertex mass...
    - Can tag single-track jets
  - Continuous variable output allows for analysis group to choose cuts:
    - optimize expected sensitivity
- Bottom line:
  - ~10% higher integrated s/\sqrt{b}:
  - ~10% stronger upper CL.
Calibration of 2012 b-Jet Tagger In Multiple Control Samples

- Calibration samples
  - Kinematic selection of $W+4,5$ jets events (di-top)
  - QCD dijets with low relative-pt electrons
    - Not an input to tagger
    - Semileptonic decay electrons
      - Enriched in $b,c$
    - Photon conversion electrons (New Method)
      - Primarily $u,d,s,c,g$
    - Examine both e-jet and opposing side jets
  - These samples produce correction factors and uncertainty estimates for simulated events
  - Resulting b-jet tag-rate corrections: $\sim 5\% \pm 4\%$
Dominant Uncertainties

- Uncertainties degrade exclusion sensitivities by ~20%

- Experimental
  - Jet energy scale (shape)
    - Vary simulated reconstructed energies
  - Luminosity
  - B-jet ID simulation
  - Lepton ID/veto

- Theoretical
  - Cross section uncertainties, K-factors
    - ~1.5 for W+jets, Z+jets
    - Extra heavy-flavor K-factor ~1.5
  - Renorm/Factorization scale (shape)
    - Vary renormalization / factorization scales
  - PDF
  - Initial/final state QCD radiation (shape)
    - Vary QCD showering parameters in simulation
WZ+ZZ: Validating Methods

- **Standard candle:** WZ+ZZ
- **Search methods identical to WH+ZH**

\[
\begin{align*}
Z \rightarrow l^+ l^- b \bar{b} & \quad \text{WZ} \rightarrow l^+ \nu b \bar{b} & \quad \text{ZZ} \rightarrow \nu \nu b \bar{b}
\end{align*}
\]
WZ+ZZ: Validating Methods

- Search for $Z \rightarrow bb$ in $llbb$, $l\nu bb$, $\nu\nu bb$
  - Identical final state as a “90 GeV Higgs”
- CDF SM expected yields for $WH, ZH, VH$:
  (Summed over all subchannels)
  - ~215 $WZ+ZZ$
  - ~591 $H \rightarrow bb$ (MH=90)
  - ~84 $H \rightarrow bb$ (MH=125)
- Measured cross section compared to NLO
  - SM $* 0.92 + 0.31 – 0.28$
  - significance of ~3.2 sigma
- DØ also sees SM-compatible VV
  - 3.28 sigma significance
WZ+ZZ: Validating Methods

- Tevatron Combined Dijet Mass Spectra
**WZ+ZZ: Validating Methods**

- Discriminants trained for WZ+ZZ, just like in Higgs Search
- Right plot shows signal ordered, rebinned, combined discriminant
- Good agreement within systematics
- Signal above systematics in rightmost region
- 4.6 sigma significance
- Measured cross section matches SM Prediction
Associated Production Channels

$ZH \rightarrow l^+ l^- b\bar{b}$

$Wl \pm v b\bar{b}$

$ZH \rightarrow \nu \nu b\bar{b}$
WW, bb Combined Searches
For CDF and DØ
Excess in H→bb

- Clear excess in CDF H→bb decays
- Largest excess is at 135 GeV
- **Not like γγ or ZZ→4l:**
  - Poor mass resolution→neighboring points correlated
- Global p-value is 2.7 sigma (Expected Signal ~1.5 sigma)
CDF and DØ Combined Searches

- DØ: Exclude $159 < M_H < 166$ GeV
- CDF: Exclude $147 < M_H < 175$ GeV
- Both have broad excess 100-150
Tevatron Run II Preliminary: Using Up to 2.4 fb⁻¹

- Median Background Only Expected
- Observed
- ± 1 σ: Background Only
- ± 2 σ: Background Only

Higgs Mass (GeV/c²) vs. 95% CL Limit/SM

April 21, 2008
Tevatron Run II Preliminary: Using Up to 4.2 fb⁻¹

March 24, 2009

- Median Background Only Expected
- Observed
- ± 1σ: Background Only
- ± 2σ: Background Only

Higgs Mass (GeV/c²)

95% CL Limit/SM
Tevatron Combination Nov. 2009

Tevatron Run II Preliminary: Using Up to 5.4 fb$^{-1}$

- November 19, 2009
- Median Background Only Expected
- Observed
- $\pm 1\sigma$: Background Only
- $\pm 2\sigma$: Background Only

Higgs Mass (GeV/c$^2$)

95\% CL Limit/SM
Tevatron Run II Preliminary: Using Up to 8.6 fb⁻¹

September 22, 2011

- Median Background Only Expected
- Observed

95% CL Limit/SM

- ± 1σ: Background Only
- ± 2σ: Background Only

Higgs Mass (GeV/c²)
Tevatron Combination Mar. 2012

Tevatron Run II Preliminary: Using Up to 10.0 fb⁻¹

March 19 2012

- Median Background Only Expected
- Observed
- ± 1σ: Background Only
- ± 2σ: Background Only

95% CL Limit/SM

Higgs Mass (GeV/c²)

100 110 120 130 140 150 160 170 180 190 200

10

1
The Winter 2012 Tevatron Combined Higgs Search

- Expect to exclude nearly everywhere
  - $1.10 \times \text{SM}$ at 130 GeV
- Exclusion:
  - 100-106 GeV
  - 147-180 GeV
- Broad excesses
  - $\sim$105-145 GeV
  - $\sim$190-200 GeV
Quantifying The Excess

- **Left:** Local p-value distribution for background-only
  - Minimum local p-value: 3.0 standard deviations
  - Global p-value with LEE factor of 4: 2.5 standard deviations
- **Right:** bb significance
Is it signal like?

- Dotted line shows 125 GeV signal injection
- Broad excess is expected.
  - (blue dotted line)
- Not mass-sensitive
- Significance
  - Global: 3.2 Std. dev
  - Local: 2.9 Std. dev.
Is it signal like?

- Find signal fraction that best fits the data:
- Data look like 125 GeV SM signal injection in shape
- $\sim 1.5$ standard deviations high
Per-channel Comparison To LHC

- **Expected Sensitivities** (Feb 2012, 125 GeV):
  - $H \rightarrow \gamma \gamma$:
    - ATLAS, CMS: $\sim 1.5 - 2xSM$
    - CDF, DØ: $\sim 10 - 13xSM$
  - $H \rightarrow WW$:
    - ATLAS, CMS: $\sim 1 - 2xSM$
    - CDF, DØ: $\sim 3.5xSM$
  - $VH, H \rightarrow bb$:
    - ATLAS (4.7/fb): $\sim 3 - 4xSM$
    - CDF, DØ (8/fb): $\sim 2 - 2.5xSM$
  - **2012**: Tevatron's most competitive search channel is $VH \rightarrow Vbb$!
H→bb Comparison To LHC

Expected and Observed Upper 95% Limits

SM VH (H to bb), February 2012, Per Experiment

Expected (125)
Observed (125)

95% Upper Limit

CMS
ATLAS
CDF
D0

Comparison To LHC
H→bb Comparison To LHC

- Tevatron Experiments:
  ~10x Higher Expected Signal Yield

Expected SM VH (H(120) to bb) Signal Yield

Per Experiment, February 2012

Number of Events

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Number of Events</th>
</tr>
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<tbody>
<tr>
<td>CMS</td>
<td>10</td>
</tr>
<tr>
<td>ATLAS</td>
<td>20</td>
</tr>
<tr>
<td>ATLAS (High-PT)</td>
<td>20</td>
</tr>
<tr>
<td>CDF</td>
<td>100</td>
</tr>
<tr>
<td>D0</td>
<td>80</td>
</tr>
</tbody>
</table>
Possibilities for Winter 2013?

- **LHC mass-sensitive channels:**
  - CMS, ATLAS: ZZ, γγ channels: Spin?

- **LHC H→bb:**
  - CMS: bb channels:
    - Updated for July:
      - Currently 1.6
      - \(~1.6 \times \sqrt{10}/\sqrt{20} = ~0.85\text{xSM}\)
    - Will soon have observation of H→ bb! (?)

- **ttH:**
  - CMS: Currently 4.6: 4.6\times\sqrt{5}/\sqrt{20} = ~2.3\text{xSM}
    - If non-SM top coupling, could have strong statement!
• ATLAS and CMS have already released constraints on coupling parameters of the X(125)
  • So far SM-like
• Tevatron in progress
  • W/Z ratio
  • V/b ratio
• Testing with WW/WZ
Interesting paper: arXiv:1208.6002v1
J. Ellis, D. S. Hwang, V. Sanz, and T. You

- $M(VH)$ can differentiate spin, parity
- Caveat: "We have not analyzed further the backgrounds in the experiments,"
  - Tevatron background are non-negligible in VH processes
- We are Investigating our sensitivity
What about models with H-like particles?
- Technicolor? (Underway)
- MSSM?

Recent combination of CDF and D0 searches for \( bh \to bbb \):
- Final state (CDF)
  - \( \geq 3 \) jets
  - \( \geq 3 \) b-tags

Analysis relies on b-jet trigger
Background is \(~100\%\) QCD

- Don't trust MC
- Use Data-driven background model
  - Templates from 2-tag data
  - Assume flavor and tag rate of third tag
- Don't trust flavor-fractions
  - Fit to data
CDF bh→bbb Analysis

- How to construct templates
  - Take data events
    - >=3 jets
    - ==2 tags
    - Order in ET
  - Now weight untagged jet
    - bbB or bBb?
    - Which jet was originally untagged
- Note that the bbb M_{j1j2} spectrum is in-between bbB and bBb
CDF bh→bbb Analysis

- Now, fit background templates in 3 dimensions
  - $M_{j1j2}$ (signal sensitivity)
  - $m_1+m_2$ (flavor sensitivity)
  - $m_3$ (flavor sensitivity)
CDF bh→bbb Analysis

- Fit Results
CDF bh→bbb Analysis

- Search Results
  - 2.8 sigma local significance at 150
  - 1.9 global
CDF bh→bbb Analysis

- Combine with D0
- Similar sensitivities, different excesses
Is That All There Is?

- Combined results
  - Two excesses sum to single, softer, broader excess
Is That All There Is?

- Comparing to the ATLAS results, mh max scenario
  - NB, ATLAS, CMS results use $h \rightarrow \mu\mu/\tau\tau$, not $bb$!
Recent Publications

- CDF $ttH$: arXiv:1208.2662 (Accepted to PRL)
- Tevatron $bbb$: arXiv:1207.2757 (Accepted to PRL)
- TeV $bbb$: arXiv:1207.2757 (Accepted to PRL)
More possibilities for 2013

- CDF still has collaborators preparing results
- Most people sharing time on other experiments
- Updating METbb analysis to new tagger
  - Different BG model, so WH/ZH tools aren't turnkey usable. (+2-3% sensitivity)
- New Higgs-related results focus on states where the Tevatron can compete
  - Low-mass decays
  - Not sensitive to pile-up
Conclusions

- For additional details see
  - Tevatron: http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_12/
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg/Results.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.html

- Thanks to everyone at CDF and DØ who contributed to this update!
- Bigger thanks to everyone who designed, built, or operated CDF or DØ!
- FNAL Computing Division: Thanks for all the computing power and software!
- FNAL Beams Division: Thanks for all the collisions!
- Photographs of Fermilab and its wildlife were taken by Reidar Hahn, FNAL VMS
Conclusions

- CDF & DØ SM Higgs searches have been updated with the complete RunII dataset
  - Expected sensitivity <1.10xSM over interesting range
  - Dominated by associated production and WW channels
- The data are
  - incompatible with background-only hypothesis,
  - compatible with signal hypothesis
  - Agreement among six channels, 2 experiments
  - global p-value of 2.5 s.d.
  - $H \rightarrow bb$ only: global 3.1 s.d.
  - Evidence for $H \rightarrow bb$!
Backup Slides
Modified Frequentist Searches (DØ)

- Define test statistic:
  - Log Likelihood Ratio: $L(s+b)/L(b)$
  - Throw pseudoexperiments generated under background or s+b hypotheses
  - Separation between LLR distributions is discovery power
  - Compute $CL(s) = CL(s+b)/CL(b)$
  - Vary assumed signal cross section until $CL(s)=5\%$
    - Signal cross section meeting this criteria is the upper limit
- CDF and DØ set limits both ways: Frequentist and Bayesian
- Two methods agree to $\sim 1\%$
Understanding Sensitivity

- Log-likelihood ratio at different masses shows what signal-like deviations across the mass range would indicate, relative to signal separation power.
Quantifying The Excess: H→bb and H→WW

- Local p-value distribution for background-only expectation.
- WW: Don't expect a significant excess
- H→bb
  - Min local p-value: 2.8 standard deviations
  - Global p-value with LEE factor of 2: 2.6 standard deviations
  - At 125: Like SM Higgs with an additional ~1.5-sigma upward fluctuation
• Exclude from 147 to 175 GeV
• Two excesses:
  • one from associated production modes
  • one at ~200 GeV.
• At 120 GeV, global p-value is 2.1-sigma
DØ: 3-lepton * 3-jet sub-channels

- Plus 3 new VH trilepton!

New analyses!

VH→VWW→ττμ
VH→VWW→eeμ
VH→VWW→μμe
• WH:
• Major background
  • W+bb, ditop, instrumental nonW.
• Added data + improved b-tagging + new triggers
• update of 3jet bin
• Best s/b: ~1:5
• 2012: 22.7→40.2 expected signal events!!!
• 1-2012/2011=~30% stronger expected limits than summer 2011
ZH Results

- **Major backgrounds:**
  - $Z+bb$, ditop

- **Improvements**
  - Added data + improved btagging
  - Better background rejection
  - Improved lepton acceptance
  - Sifted background discrimination

- **2011 to 2012:**
  - Doubled integrated $s/\sqrt{b}$!
  - Best $s/b$: $\sim 1:1$
  - $1-2012/2011 = \sim 34\%$
    - Stronger expected limits than $ZH$ summer 2011
• Consider a study performed by injecting MH=125 GeV Higgs signal to our search,
  • luminosity scaled so the excess is 3 s.d. above the background prediction.
The Path To SM Sensitivity

- CDF has reached ~SM Sensitivity
  - Why now?
  - 10/fb and steady progress
    - more decay channels
    - acceptance in old channels
    - Improved reconstruction
    - Improved discrimination
- Since 2007:
  - Factor of ~2 improvements beyond additional data
- Since July 2010:
  - Factor of ~1.5 beyond additional data at low mass
CDF: New Jet Shape Systematics

- Z+1Jet balancing studies performed
- Poor description of Z-jet balance seen in gluon-like jets.
  - MC gluon jets harder than data in ET by ~2xJES
  - MC quark jets well described
- Origin of mismodeling still under investigation
  - Affects jet energies, dijet mass spectrum of untagged jets
- Negligible effect on tagged samples
- For 2012 results, MC simulation has been corrected for this effect
- Change to expected or observed limits far below other systematics
- For more information:
Effect of Improved Tagging (WH)

- Significant effort to optimize tagging categories and thresholds for loose/tight tagging selections
- 11% gain in $S/\sqrt{B}$ means expected limits lower by $\sim$11%.

<table>
<thead>
<tr>
<th>Tagging Category</th>
<th>2011</th>
<th>S/\sqrt{B}</th>
<th>2012</th>
<th>S/\sqrt{B}</th>
</tr>
</thead>
<tbody>
<tr>
<td>SecVtx+SecVtx</td>
<td></td>
<td>0.228</td>
<td></td>
<td>0.266</td>
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<tr>
<td>SecVtx+JetProb</td>
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<td>0.160</td>
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<td>0.200</td>
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<tr>
<td>SecVtx+Roma</td>
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<tr>
<td>Single SecVtx</td>
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<td>Sum</td>
<td></td>
<td>0.331</td>
<td></td>
<td>0.369</td>
</tr>
</tbody>
</table>
ZH Results: Comparison to 2011
ZH Results: Comparison to 2011
**Improved Discrimination**

- ZH Analysis now sifts events into 4 categories
  - Non-Z
  - Z+lf
  - VV
  - Z+bb
- Each category then separated for ZH
- Resulted in ~10% improvement over previous discriminant primarily due to removal of VV from ZH region
Improved Discrimination

- ZH Analysis now sifts events into 4 categories
WH: Comparison to 2011 Results

- Overall shape comparable to 2011 2-jet bin of WH
Comparing Summer 2011 Limits

Winter 2012

Summer 2011