The Search For The Higgs Boson
In The Complete Run II Dataset With CDF

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Goal: Direct Evidence for the SM Higgs Boson

Motivation

2011 Search Status

The Tevatron, CDF

SM Higgs Production & Decay at the Tevatron

Recent Advancements in Search Techniques

Prospects for Full Dataset Results

The Future
**Theoretical Motivation**

- Gauge invariance suggests massless W and Z bosons
  - W, Z observed to be massive
- In SM, W&Z observable mass via electroweak symmetry breaking
- Ground breaking work on EWSB:
- Proposed mechanism of EWSB predicts an additional observable scalar particle.
Experimental Status

- Resulting boson mass is unpredicted by theory
  - Mass determines production and decay rates (next slide)

- Indirect constraints (MW, Mtop) prefer a “light” SM Higgs Boson
  - New CDF 2012 W mass! (B. Jayatilaka, La Thuile)

- Direct Searches: Exclusions of MH:
  - LEP < 114 GeV
    - arXiv:0602042v1
  - Tevatron [156,177] GeV
    - arXiv:1107.5518
  - LHC [~127, 600] GeV
    - arXiv:1202.1408 (ATLAS)
    - arXiv:1202.1488 (CMS)
Tevatron: Powerful in H→bb

- **Expected Sensitivities**
  (January 2012, 125 GeV):
  - H→bb:
    - ATLAS, CMS: ~4.3xSM
    - CDF, D0: ~2xSM
  - H→γγ:
    - ATLAS, CMS: ~1.5-2xSM
    - CDF, D0: ~10-13xSM
  - H→WW:
    - ATLAS, CMS: ~1-2xSM
    - CDF, D0: ~3.5xSM

- **Tevatron's strength in the light-SM-Higgs scenario is the branching fraction of H to bb!**

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ARXIV:1202.4195
The Tevatron, Batavia IL, USA

- Superconducting storage ring
  - 1 beampipe, 1 km radius
- Run II: Mar 2001-Sept 2011
- Provided pp collisions at 1.96 TeV to CDF/DØ
  - 36x36 bunches
  - ~E10-E11 particles per bunch
  - ~21μs per revolution
  - ~1.5 MJ beam energy
- Thanks to FNAL Beams Division!
  - Peak inst.: >4.2E32 cm⁻²/s
  - ~70/pb delivered/week
  - ~12/fb delivered/exp.
CDFII: a Multipurpose Collider Detector

- ~5K tons (~2.5K central only)
- ~10 m each direction
- ~100 Hz readout
- ~720 K silicon tracker readout channels
- Muon chambers: |\( \eta \)|<1.5
- Silicon tracking |\( \eta \)|<2-2.5
- Drift cell tracker 1.4 Tesla B field, |\( \eta \)|<1.1
- Pb/Cu/scint calor. |\( \eta \)|<3.2
  - JES uncertainty 2-3%
SM Higgs Production at The Tevatron

Associated Production:
Most Sensitive at $M_H < 135$

Direct Production:
Most Sensitive at $M_H > 135$
Some of the Many Final States in Associated Production

CDF Candidate
ZH → νν bb
Data Event

Jet

Missing Energy

CDF Candidate
ZH → eebb
Data Event

Jet

CDF Candidate
WH → eνbb
Data Event

Jet
1 SM Higgs, Many Decays

For the 2012 CDF Winter results:
- SM predicts ~167 Higgs (125 GeV) events *reconstructed and selected*
- SM background of ~200K

Partitioned over many final states
- Low (<150 GeV) mass
  - WH, ZH, METbb, ttH, γγ, VBF → bbjj
- High (>150 GeV) mass
  - WWW, WWZ, WW, ZZ, τ-decays, full/semi-leptonic...

16 CDF analyses:
- 93 orthogonal sub-channels.

Small signal on diverse background
- Maximizing signal acceptance is key
Quantitative Statements About Small Signals

- **Reconstruct, select events**
  - Simulate background processes

- **Optimize signal significance**
  - Avoid cutting any signal events!
  - Discriminant distribution:
    - Dijet mass
    - Neural network, BDT, Matrix element probability
  - Background rich regions can be used to constrain backgrounds underneath signal, and constrain systematic uncertainties

\[ S/B \text{ is Really Small} \]
Quantitative Statements About Small Signals

- Bayesian Method:
  - Compare 2 models:
    - BG-only
    - BG+signal hypotheses
  - Compute Poisson Likelihood
    - Compatibility of data with each hypothesis
  - Compute posterior probability density:
    - Cross section scaling: \( R = \frac{\sigma}{\sigma(\text{SM})} \)
      - Flat Prior: \( R = [0, \text{Large #}] \)
    - Nuisance parameters:
      - Detector response, background cross sections, PDFs, etc.
  - Integrate likelihood over nuisance parameters:
    - Produces posterior probability as function of \( R \) alone

Upper Limit
Exclude: < 1xSM

Observe?
Quantitative Statements About Small Signals

- Perform this analysis for each assumed Higgs Mass:
  - For data (Observed upper limit)
    - Construct ensemble of *background-only* pseudoexperiments (Expected sensitivity)
      - Each has same statistical uncertainty as data
    - Shaded bands show *background-like* statistical and systematic excursions
CDF: Relentless Pursuit

- CDF analyses improve far beyond adding data.
  - Improvements made are beyond those projected in 2007!
  - \([(2007 \, \text{Exp})/1.5, \, (2007 \, \text{Exp})/2.25]\)

- Adding data alone to the 2007 analyses would have required >30/fb to reach SM MH=115 cross section sensitivity!

![Graph showing expected limits and SM cross sections over time](attachment:image.png)
CDF Combined Higgs Search: 2011

- Better than 2xSM over non-excluded range
  - Broad excess 100-150 GeV
    - Not significant (~0.5-\(\sigma\))
    - \(M_{jj}\) resolution \(\sim\) +/-15 GeV
  - Most sensitive searches at 125 GeV, \(\sim\)equal:
    - \(WH\rightarrow l\nu bb\)
    - \(ZH\rightarrow llbb\)
    - \(WH+ZH\rightarrow METbb\)
    - \(H\rightarrow WW\rightarrow l\nu l\nu\)

- Sensitivities add roughly as inverse quadrature
New Major Improvements

- Summer 2011 results used 7.5-8/fb
  - Luminosity quoted depends on each final state
  - Full CDF dataset results (9.4-10/fb) presented here

- Improved b-jet identification:
  - More acceptance: ~10-15% better sensitivity in WH, ZH
  - less background

- Inclusive online selection

- More efficient offline selection
  - See H→WW presentation (R. St. Denis)

- Improved background discrimination
Identifying Jets from Hadronic Higgs Decays

- 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 jets with only one charged particle track
  - Continuous variable output allows for analysis group to choose cuts:
    - Optimize expected sensitivity
  - For identical false-positive rates of previous taggers, b-jet efficiency:
    - Tight: 38.6→53.6%
      - False Positive: 1.4%
    - Loose: 47.1→59.3%
      - False Positive: 2.8%
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: ~5%±4%
Deployment of 2012 NN b-jet ID

- After calibration of LF and b-jet responses
  - Examine data/MC yields in samples of W+jets
    - W+1jet: largely u,d,s,c,g
    - W+4,5 Jet: Di-Top
      - real b-jets
    - W+2,3: Mixture
  - Good agreement overall
    - ~40% K-factor uncertainties for W+jets
Improved Discrimination

- Both WH and ZH now performing Multi-stage discriminants:
- Gets background out from under signal
- Prevents the need for cuts
  - 4% gain in WH 3-jet bin (removing di-top)
  - ~7% gain in ZH by separating di-top and ZZ

![Diagram](image.png)
WZ+ZZ: Validating Methods

- CDF detects SM-compatible semi-leptonic WZ and ZZ over a tagged background of dijets.
  - $l\bar{l}bb, l\nu\bar{l}bb$
  - Identical final state as a “90 GeV Higgs”
  - See upcoming talks at Moriond EWK and QCD by J. Vizan Garcia and J. Sekaric
- SM expected yields for WH,ZH,VH:
  (Summed over all subchannels)
  - $\sim 215$ WZ+ZZ
  - $\sim 591$ H→bb (MH=90)
  - $\sim 84$ H→bb (MH=125)
- Measured Cross Section to be released next week!
- Additionally, The newly generated 90 GeV Higgs signal MC will test our dijet modeling lower in Mjj than ever before.
2011→2012 Limit Comparisons

● WW, METbb:
  - Biggest improvement is data update
    - ~11-12% sensitivity improvement everywhere
  - Overall behavior of limits should not dramatically change
2011→2012 WH Limit Comparisons

- Added data + improved tagging + new triggers + update of 3-jet bin:
  - 22.7→40.2 Expected Signal Events!!!
  - Roughly 30% stronger expected limits
ZH Analysis:
Total sensitivity improvement after systematics: 58% @ MH=120
- New Data: ~11%
- Improved lepton Acceptance: ~8%
- New b-tagger: ~12%
- Other Improvements ~5-10 each%
  - Exclusive Z+2,3-jet categories
    - Previously had inclusive 2-jet category
  - Expert ZH, ZZ separator
  - Higher threshold on jets
  - Dijet mass resolution: 12%→9.6%
    - Improved MET calculation,
      less sensitive to underlying event
2011→2012 ZH Limit Comparisons

- Total Yield:
  - 5.3(1388)→7.2(1211) expected S(B) events.
    - Per-event Tagging Efficency was 60%, now is 69%
    - Better rejection of BG
  - Double integrated signal significance!
  - EPS 2011 Limit Median is at 2012 +1-σ!
2011→2012 Full Limit Comparisons

- Major gains in expected sensitivity from data and tagging
  - ~30% from 115-125
  - ~15% at high mass
  - CDF expects to be sensitive to at most $\sqrt{2}$*SM @ MH=130
  - Expects to exclude [152-175] GeV
● Next Week:
  - Release observed limits next Weds at Moriond!
  - **Tevatron Combination** talk at Moriond EWK by Wade Fisher!
  - Potential for ~1xSM exclusion sensitivity

● Near Future
  - Consolidate improvements across all channels
    - >5% improvement in 125 GeV sensitivity still possible
  - Publish PRL/PRD/NIM for analyses/methods
Conclusions

● The CDF Collaboration has produced Higgs searches with expected sensitivities a factor of 2 better than 2007 beyond luminosity additions!

● CDF is sensitive to $<\sqrt{2}\times\text{SM}$ Everywhere
  - $2\times\text{CDF}$ would have $>25\%$ chance of 3-sigma!

● Tevatron Leads in $H\rightarrow bb$

● The Tevatron full dataset combined Higgs search will be exciting!
Conclusions

- For additional details see
  - Tevatron: http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_12/
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg/Results.html
  - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.html

- Thanks to everyone at CDF who contributed to this update!
- Bigger thanks to everyone who designed, built, or operated CDF!
- 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
Thank you for your attention

Questions?
CDF JES

- JES

![Graph showing uncertainties on JES against corrected transverse momentum (p_T^corr) in GeV/c.]
FIG. 1: Kinematic coverage of the DIS and collider $pp$-$p\bar{p}$ experiments. For $pp$ and $p-\bar{p}$ colliders, the Bjorken $x_1$ and $x_2$ of the interacting quarks are related to the mass $M$ of the Drell-Yan pair and its rapidity $y$ as $x_{1,2} = M/\sqrt{S} \exp(\pm y)$ where $S$ is the center of mass energy squared for the experiment.
Comparing The Higgs Search To Single-Top Discovery

- Same machinery was run for the Single Top obs/discovery 2008-9

- Currently going through same steps with WZ/ZZ→ leptons+HF to validate low-Mass Higgs Search
Comparison To EWK Diboson