Searches for a Light Higgs Boson at the Tevatron

Artur Apresyan
Purdue University
On behalf of the CDF and DØ Collaborations

Les Rencontres de Physique de la Vallée d'Aoste, La Thuile 2009
Standard Model: a very successful theory
- Explains most of known phenomenology of particle physics

Last missing piece: the Higgs boson, has yet to be detected
- In a sense, the fact that (W±, Z) are massive is a testament of Higgs–like mechanism at work

The SM does not predict the mass of Higgs boson
- Need to be determined from experiment

Direct observation of Higgs boson is needed
- LEP excluded SM Higgs boson with $M_H < 114.4$ GeV/$c^2$ at 95%CL

Higgs boson enters into radiative corrections
- Constrain the mass of Higgs boson from precision measurements
- Logarithmic dependence causes only weak constraints
- With latest top/W mass from Tevatron: $M_H < 154$ GeV/$c^2$ at 95% CL
The only machine currently capable to directly probe the Higgs sector above LEP limit

- Proton–antiproton collisions at 1.96 TeV center–of–mass energy
- Two–multipurpose detectors: CDF and D0, stable operations
Tevatron Experiments
Tevatron Experiments

Luminosity (pb^{-1})

Analyses in this talk: 1–4.2 fb^{-1}

- Delivered
- Acquired
100 times more data than used for Top quark discovery!

\[ L = \int L \cdot dt \]
The gluon fusion is the dominant production mode: $\sigma \sim 1.1 - 0.1$ pb

W/Z associated production next most frequent mode: $\sigma \sim 0.2 - 0.01$ pb
The gluon fusion is the dominant production mode: $\sigma \sim 1.1 - 0.1 \text{ pb}$

- **W/Z associated** production next most frequent mode: $\sigma \sim 0.2 - 0.01 \text{ pb}$

- $gg \rightarrow H \rightarrow b\bar{b}$: dominates
  - Not feasible, swamped by QCD

- Rely on $VH$: $W/Z$ decays provide signature to increase $S/B$

- Additional modes, e.g. VBF, ttH, $H \rightarrow \gamma \gamma$
High Mass: $M_H \gtrsim 135 \text{GeV/c}^2$
- $gg \rightarrow H \rightarrow W^+W^-$ dominates
- Leptonic decays of the $W$'s help to suppress backgrounds
- Associated modes also contribute
- See next talk by H. Greenlee!

- The **gluon fusion** is the dominant production mode: $\sigma \sim 1.1 - 0.1 \text{ pb}$
- **W/Z associated** production next most frequent mode: $\sigma \sim 0.2 - 0.01 \text{ pb}$
The challenges of the Higgs searches

- Hadron colliders: most promising for discovery
  - Challenging experimental environment
  - QCD production: orders of magnitude higher than signals

- Many background processes are not yet well-measured/understood
  - Continuously reaching new landmarks
  - Single top evidence.
  - Observations of diboson production: WW, WZ, ZZ
  - Production of h.f. jets in association with W/Z

- Higgs boson production is very rare!
Measuring small signals at Tevatron

$B^0_S$ oscillation frequency

![Graph showing D$^0$ Run II Preliminary results with data plots and sensitivity]

Total cross section in $1 \text{fb}^{-1}$:
- $m_{bb}: 1 \times 10^{11}$
- $W$: $6 \times 10^6$
- $Z$: $6 \times 10^5$
- $t\bar{t}$: $14,000$
- Single top: $5,000$
- Higgs (ZH + WH): $100$
- $f_{bb}$: $\sim 10$

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Measuring small signals at Tevatron

CDF II preliminary

$\int L dt = 200 \text{ pb}^{-1}$

$M_W = (80349 \pm 54_{\text{stat}} \, \text{MeV})$

$\chi^2/\text{dof} = 59 / 48$

**W boson mass**

<table>
<thead>
<tr>
<th>Total inelastic</th>
<th>Events in 1 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mb</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td></td>
</tr>
<tr>
<td>$\mu b$</td>
<td>$6 \times 10^6$</td>
</tr>
<tr>
<td>$W$</td>
<td>$6 \times 10^5$</td>
</tr>
<tr>
<td>$Z$</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$14,000$</td>
</tr>
<tr>
<td>single top</td>
<td>$5,000$</td>
</tr>
<tr>
<td>fb</td>
<td>$100$</td>
</tr>
<tr>
<td>Higgs (ZH + WH)</td>
<td>~$10$</td>
</tr>
</tbody>
</table>

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Measuring small signals at Tevatron

Z$\rightarrow$\(\mu\mu\) cross-section

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**DØ Run II Preliminary**

- **Entries/2 GeV**
  - Data
  - Monte Carlo
  - Background

**Total cross section**

<table>
<thead>
<tr>
<th>Process</th>
<th>Events in 1 fb$^{-1}$</th>
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<tr>
<td>mb</td>
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<tr>
<td>bb</td>
<td></td>
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<tr>
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Measuring small signals at Tevatron

CDF Run II Preliminary (2.9 fb⁻¹)

Data
Fitted \( \bar{t}t \)
Fitted Bkg

\( \chi^2/\text{Ndof} = 20.2 / 22 \)

Prob = 0.569

Events/(5.0 GeV)

0
10
20
30
40
50
60

100
150
200
250
300

Events/(5.0 GeV)

0
10
20
30
40
50
60

Fitted Bkg

≥ 2 tags events \( m_t^{\text{rec}} \)

Top quark mass

Events in 1fb⁻¹

Total inelastic

- \( b\bar{b} \)
- \( \mu b \)
- \( W \)
- \( Z \)
- \( \bar{t}t \)
- single top
- Higgs (ZH + WH)

1x10¹¹
6x10⁶
6x10⁵
14,000
5,000
100
~10

Prob = 0.569

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Measuring small signals at Tevatron

EW production of single top quarks

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“Well, either we've found the Higgs boson, or Fred's just put the kettle on”
The Higgs search strategy

- Efficient triggers to keep most of potential Higgs candidates
  - High $P_T$ charged leptons: $e$ or $\mu$ to select leptonic decays of the $W/Z$
  - MET+Jets: to select $ZH \rightarrow \nu\nu b\bar{b}$ or $WH \rightarrow \ell\nu b\bar{b}$ (the lepton is not identified)
  - Lepton+Track for $\tau\tau$-modes or MET+Jets for $WH \rightarrow \tau\nu b\bar{b}$

- Increase signal yields:
  - Improve lepton acceptance by improving the $e/\mu$ ID
  - More efficient $b$-tagging algorithms: crucial for low-mass Higgs: $H \rightarrow b\bar{b}$ dijet mass resonance
  - Better understand the calorimeter response: Dijet mass resolution

<table>
<thead>
<tr>
<th>Events per fb$^{-1}$</th>
<th>ZH$\rightarrow$llbb</th>
<th>WH$\rightarrow$lnbb</th>
<th>ZH$\rightarrow$vvbb</th>
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<tbody>
<tr>
<td>Signal produced</td>
<td>5</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Signal accepted</td>
<td>$\sim1$</td>
<td>$\sim3$</td>
<td>$\sim2$</td>
</tr>
<tr>
<td>Signal/Background</td>
<td>$\sim1/200$</td>
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- Looking for a resonance in Dijet mass
  - Backgrounds are large in size, with large uncertainties
  - Use multivariate techniques to maximally separate signal from backgrounds
    *Neural Networks, Matrix Element, Boosted Decision Tree, etc...*
The Higgs search strategy

- Efficient triggers to keep most of potential Higgs candidates
  - High $P_T$ charged leptons: $e$ or $\mu$ to select leptonic decays of the $W/Z$
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<th>$ZH\rightarrow l\nu b\bar{b}$</th>
<th>$WH\rightarrow l\nu b\bar{b}$</th>
<th>$ZH\rightarrow \nu\nu b\bar{b}$</th>
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- The statistical significance of single channels is not enough
  - Combine all the channels within CDF and D0, and combine CDF and D0
  - Collect as much data as possible: improve triggers, data-taking efficiency
Analysis tools: $b$–jet identification

- **Dijet Invariant Mass:** resonance from $H \rightarrow bb$

- Exploit long lifetime of B-mesons: $b$-tagging
  - Identify signal with jets from $b$-quarks
  - Suppress light flavor backgrounds ($u, d, s$ or $g$)
  - Improves S/B to from 1:1000 to ~1/50-1:100

- Various algorithms used by CDF and D0
  - Identify the displaced vertex from the decay of B
  - Exploit multiple features of b-jets: NN tagging
  - Probability that the tracks come from prime vtx: JetProb
  - High $b$-tagging efficiency: 40-70%
Analysis tools: lepton identification

- Identify the decays of the W/Z
  - Electrons: tracks matched to shower max in ECAL
  - Taus: tracks matched to a calorimeter cluster
  - Muons: tracks matched to muon chambers

- Expand the lepton coverage
  - Interplay between sub-detectors: cover the “holes”
  - Include forward detectors to extend coverage

- Excellent MET triggers:
  - Select events with neutrinos and charged leptons that failed to ID
  - Good understanding of the detector
  - Efficiently remove events with fake MET
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Extended muon coverage at CDF

WT mass with W→τν (D0)
Maximize discriminating power: global kinematics of signal & backgrounds
- Machine learning techniques: Neural Networks (NN), Boosted Decision Trees (BDT), etc.
- Calculate the probabilities for event to come from signal from LO matrix element (ME)

Multivariate techniques help to improve the sensitivity
- Remove large, uncertain backgrounds to reduce large systematic effects
- Increase the significance of signal
- Test these methods in well-known processes: e.g. ttbar

Evidence for semi-leptonic WW/WZ at D0: Random Forest (RF) technique
- Dijet mass scan yields 2.9s.d. (expected), output of RF improves sensitivity to 3.6s.d.
- Observed signal significance 4.4s.d.: $\sigma_{\text{meas}} = 20.2 \pm 4.5$ pb ($\sigma_{\text{theory}} = 16.1 \pm 0.1$ pb)
Two charged leptons: \( ZH \rightarrow \ell^+ \ell^- b\bar{b}, \ell = e, \mu \)

- Fully reconstructed final state
  - Two resonances: \( H \rightarrow bb \) and \( Z \rightarrow ll \)
  - The dilepton mass cut \( M_{ll} \approx M_Z \)
- Dominant backgrounds:
  - \( Z + \text{jets} \) (irreducible \( Z + bb \)), top, dibosons
- Small \( \sigma \times \text{Br} \): \( \sim 1 \) event/fb\(^{-1}\)
  - Acceptance is crucial: employ loose \( b \)-tagging
  - Analyze events with at least one \( b \)-jet

Special techniques:
- Correct jet \( E_T \)'s using MET\(\rightarrow\) JER improves from 18% to 11%
- Lepton coverage: stubless \( \mu \)'s, forward \( e \)'s: improve limit by 10%
Two charged leptons: $ZH \rightarrow \ell^+\ell^-b\bar{b}$, $\ell = e, \mu$

- Improve analysis sensitivity:
  - CDF: Matrix Element and 2D NN
  - DØ: NN for $ee$ and BDT for $\mu\mu$ channels

- $2.7$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lumi (fb$^{-1}$)</th>
<th>Signal Evts</th>
<th>Exp limit</th>
<th>Obs limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF ME ($M_H=120$)</td>
<td>2.1</td>
<td>1.4</td>
<td>15</td>
<td>14.2</td>
</tr>
<tr>
<td>CDF NN</td>
<td>2.7</td>
<td>2.1</td>
<td>9.9</td>
<td>7.1</td>
</tr>
<tr>
<td>DØ BDT</td>
<td>2.3</td>
<td>2.1</td>
<td>12.3</td>
<td>11.0</td>
</tr>
</tbody>
</table>
One charged lepton: $WH \rightarrow \ell v b\bar{b}$, $\ell = e, \mu$

- “Large” $\sigma \times Br$, clean signature
  - Acceptance to about 3–4 events/fb$^{-1}$
  - High $P_T$ leptons, MET and $\geq 2$ jets
- Dominant backgrounds:
  - $W+bb$, top, diboson, QCD multi-jet

Special techniques:
- CDF/DØ: at least 1 b-tag, loose double-tag
- CDF/DØ: ME to discriminate signal from bckg
- CDF: loose muons, NN-based jet correction
- DØ: forward electrons, events with 3 jets
One charged lepton: $WH \rightarrow \ell\nu b\bar{b}$, $\ell = e, \mu$

- Improve analysis sensitivity:
  - **CDF**: BDT + NN $\rightarrow$ SuperDiscriminant using NEAT
  - **DØ**: NN for events with 2 jets, Dijet Mass for 3-jets

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<tr>
<td>CDF NEAT</td>
<td>2.7</td>
<td>8.3</td>
<td>4.8</td>
<td>5.6</td>
</tr>
<tr>
<td>DØ NN</td>
<td>2.7</td>
<td>13.3</td>
<td>6.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Zero charged leptons: $VH \to E_T^\tau b\bar{b}$

- Large signal acceptance: $ZH \to \nu\nu b\bar{b}$ / $WH \to \ell\nu b\bar{b}$
  - Acceptance to about $3–4$ events/fb$^{-1}$
  - Large MET and $\geq 2$ jets
  - Information of $W/Z$ missed: no strong constraints
- Dominant backgrounds:
  - QCD with fake MET, $W/Z+jets$, top, diboson

- Special techniques:
  - CDF/DØ: data-driven QCD model, track $M_{PT}$
  - CDF: at least 1 $b$–tag, 3 tagging channels, NN–based event selection ($QCD$ rejection $NN$), track–based jet corrections
  - CDF: accept $WH \to \tau\nu b\bar{b}$ with hadronic $\tau$
Zero charged leptons: \( VH \rightarrow E_T b\bar{b} \)

- Improve analysis sensitivity:
  - **CDF**: NN with separate training for 2 and 3 jets
  - **DØ**: BDT for double tagged sample

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<tr>
<td>CDF NN</td>
<td>2.1</td>
<td>7.5</td>
<td>5.6</td>
<td>6.9</td>
</tr>
<tr>
<td>DØ BDT</td>
<td>2.1</td>
<td>3.7</td>
<td>8.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Other channels: $H \rightarrow \tau\tau + 2 \text{jets}$, $WH \rightarrow \tau \nu b\bar{b}$

- Analyze all feasible channels
  - Additional sensitivity in combination

- CDF: $H \rightarrow \tau\tau + 2 \text{jets}$
  - Largest backgrounds: QCD fakes, $Z \rightarrow \tau\tau + \text{jets}$
  - Sensitivity to $WH/ZH$, VBF, ggH
  - Train 3 NN targeting specific backgrounds

- DØ: $WH \rightarrow \tau \nu b\bar{b}$: hadronic $\tau + \text{MET} + b$–jets
  - Largest backgrounds: $W + \text{jets}$, top, multijet
  - Require 2 $b$–tagged jets
  - Scan the Dijet Mass distribution

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<tr>
<td>CDF $\tau\tau + 2\text{jets}$</td>
<td>2.0</td>
<td>5.3</td>
<td>24.8</td>
<td>30.5</td>
</tr>
<tr>
<td>DØ $WH \rightarrow \tau \nu b\bar{b}$</td>
<td>1.0</td>
<td>0.2</td>
<td>42.1</td>
<td>35.4</td>
</tr>
</tbody>
</table>
Additional channels

- **DØ: ttH→lubbbbqq** (2.1 fb⁻¹)
  - Scan the distribution of H_T: scalar sum of jets
  - 4 or 5 jets, 1–3 b-tagged jets
  - Exp (Obs) Limit: 45.3 (63.9)*SM

- **DØ: H→γγ** (4.2 fb⁻¹)
  - Scan the Diboson mass
  - Exp (Obs) Limit: 18.5 (15.8)*SM

- **CDF: VH→qqbb** (2.0 fb⁻¹)
  - Good signal acceptance: large BR(W/Z→qq)
  - Employ ME technique, 2 b-tagged jets
  - Exp (Obs) Limit 37 (38)*SM
Increase the Tevatron reach: statistically combine all search channels
- Effectively **double** the analyzed luminosity
- **Systematic uncertainties**: nuisance parameters with truncated Gaussian constraints
- Set 95% C.L. upper limits on the Higgs boson production cross-section

<table>
<thead>
<tr>
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<th>DØ</th>
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<tbody>
<tr>
<td>Exp limit</td>
<td>3.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Obs limit</td>
<td>3.8</td>
<td>5.3</td>
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CDF and $\text{DØ}$ combined limits

- Increase the Tevatron reach: statistically combine all search channels
  - Effectively **double** the analyzed luminosity
  - **Systematic uncertainties**: nuisance parameters with truncated Gaussian constraints
  - Set 95% C.L. upper limits on the Higgs boson production cross-section

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<th>at $M_H = 115$ GeV/c²</th>
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<th>Obs limit</th>
</tr>
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<tr>
<td>CDF</td>
<td>3.2</td>
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Experiments are continuously improving analysis technique:
- Progress much faster than only from additional data
- Sensitivity increased factor of 1.5 w.r.t last year: equivalent of more than double luminosity
- Should be able to probe SM cross-sections with full Tevatron luminosity
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With additional factor 1.5 improvement in analysis technique
Experiments are continuously improving analysis technique:

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- Should be able to probe SM cross-sections with full Tevatron luminosity
Tevatron: luminosity prospects

Luminosity projection curves for Run II

- Tevatron running very well
  - Expect to have > 7.8 fb⁻¹/exper by the end of 2010
  - More than 6.6 fb⁻¹/experiment of good data
Summary

- Accelerator and the experiments performing very well
- Broad program of Higgs physics
  - Search for signal in all feasible channels
  - Quick turn-around to analyze additional accumulated data
- Combined Tevatron sensitivity below $3\times\text{SM}$ (for $MH=115\text{GeV}$)
  - Steadily getting close to being able to probe Standard Model Higgs production
- Analysis improvements in progress:
  - Enhanced $b$-tagging efficiency, new triggers, additional lepton categories
  - Additional tools to increase statistical sensitivity: optimize multivariate tools
  - Reduce background uncertainties: systematics will start to be limiting
- The Tevatron does have a chance to find an evidence of Higgs
  - A flow of improvements and close collaboration between CDF and DØ are crucial
Backup
The CDF and D0 detectors

- Tracking: silicon tracker + drift chamber
  - CDF $|\eta| < 2$ scint
  - D0 $|\eta| < 3$
- Calorimeters: central, wall, plug coverage:
  - CDF $|\eta| < 3.6$
  - DO $|\eta| < 4.2$
- Muon coverage $|\eta| < 2$
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- Calorimeter
- Shielding
- Toroid
- Muon Chambers
- Muon Scintillators

\[ \eta = 0 \]
\[ \eta = 1 \]
\[ \eta = 2 \]
\[ \eta = 3 \]

- Time-of-Flight Detector
- SOLENOID
- COT

- SVX II
  - 5 LAYERS
- INTERMEDIATE SILICON LAYERS

End Plug Calorimeter
End Wall Hadron Calorimeter

\[ \eta = 1.0 \]
\[ \eta = 2.0 \]
\[ \eta = 3.0 \]
Data taking efficiency ~85–90%
- ~5% due to trigger dead time
- ~5% from beam conditions
- ~5% occasional detector related downtime
The searches for the Higgs boson

- The Higgs mechanism is testable in experiments
  - Direct observation of the Higgs boson is needed
  - The interactions of the Higgs boson are predicted by theory, but not its mass

- Searches for the Higgs boson in 70’s–80’s
  - Before the LEP era searches were sensitive to $M_H \leq 5\text{GeV}$

- LEP provided the most stringent bounds for SM Higgs: $M_H > 114.4\text{GeV}$

Indirect searches:

- Constraints from fitting EW data
  - $M_H = 84^{+34}_{-26} \text{ GeV}$
  - $M_H < 154\text{GeV}$ at 95%CL

- Indirect constraints provided first hints of top mass before discovery
  - Predicted to be $180\pm12\text{GeV}$
Indirect constrains from EW parameter fits provided first hints of top quark mass
- Will this repeat for Higgs?
Setting the limit

- Use Bayesian and frequentist approach:

  - Bayesian
    \[ L(R, \vec{s}, \vec{b} | \vec{n}, \vec{\theta}) = \prod_{i=1}^{Nc} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}/n_{ij}} \times \prod_{k=1}^{n} e^{-\theta_k^2/2} \]

  - Frequentist (CL$_s$)
    \[ LLR_n = 2 \sum_{i=1}^{N} (s_i - n_i \log (1 + \frac{s_i}{b_i})) \]

- If the excess is significant after combination, do more checks to make sure not statistic fluctuation.
- If no excess, set 95% CL upper limit vs mH