Higgs Searches at the Tevatron

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Outline:

• Introduction.
• SM Higgs Results.
• Non-SM Higgs Results.
• Summary.
Indirect Constraints

- Tevatron experiments can set indirect constraints on the Higgs mass via precision measurements of the $W$ boson and top quark masses.
- Not the focus of this talk.
Standard Model Higgs

- For $m_H \lesssim 140$ GeV:
  - $H \rightarrow b\bar{b}$ dominates.
  - $gg \rightarrow H$ hopeless due to QCD background.
  - Look for associated $W/Z$ production with leptonic decays.
- For higher masses:
  - $H \rightarrow WW$ dominates.
  - Can look for $gg \rightarrow H \rightarrow WW$.
- Cross section $\sim 0.1$ pb.
- Other channels:
  - $Hb\bar{b}$, $Ht\bar{t}$ have spectacular signatures, but $\sigma \sim 5$ fb.
- SM extensions may enhance $hb\bar{b}$, $H \rightarrow \gamma\gamma$.
Fermilab Tevatron

- Until the LHC turns on, this is the only place in the world capable of probing the Higgs sector.
- Collides \( p \) on \( \bar{p} \) at \( \sqrt{s} = 1.96 \) TeV.
- Bunch spacing: 396 ns.
  (36x36 bunches)
- Peak luminosity: \( 80–100 \times 10^{30} \).

- Exceeded luminosity goals for 2004!
- Total delivered: \( > 600 \) pb\(^{-1} \).
Both feature: tracking in central $B$-field, silicon vertex tracker, outer tracking, calorimetry, muon system.
DØ
$WH \rightarrow \ell \nu b\bar{b}$

**Signal**

- “Golden” channel for the Tevatron experiments.
- Final state:
  - High-$p_T$ lepton.
  - Large $E_T$.
  - Two $b$-jets.
- Essential capabilities:
  - Good, efficient lepton ID.
  - $b$-tagging.
  - $m(b\bar{b})$ resolution.

**Backgrounds**

- Light quark production: $p\bar{p} \rightarrow jjj \ldots$
- Heavy flavor production: $p\bar{p} \rightarrow b\bar{b}j \ldots$
- $W +$ light jets: $p\bar{p} \rightarrow Wjj$
  - Suppress with lepton, $E_T$, $b$-tagging cuts.
- $t\bar{t}$: $p\bar{p} \rightarrow \ell\nu q\bar{q}b\bar{b}$, $p\bar{p} \rightarrow \ell\nu\ell\nu b\bar{b}$.
  - ↑ A significant background!
  - Veto on extra leptons or jets.
- $Wb\bar{b}$ ($Wc\bar{c}$) ← Major background!
- $p\bar{p} \rightarrow t\bar{b} \rightarrow \ell\nu b\bar{b}$
- $p\bar{p} \rightarrow WZ \rightarrow \ell\nu b\bar{b}$
  - Look for $m(b\bar{b})$ mass peak.
  - Other event kinematics.
• Examples of $W/Z \rightarrow$ lepton plots for $e$, $\mu$, and $\tau$.
$B$ tagging

- Being able to identify jets containing $b$ quarks is essential for many Higgs analyses.
- E.g., separate $Wb\bar{b}$ from $Wjj$.
- Can look for semileptonic $b$ decays: $b \to (e/\mu)\nu c$, but branching ratio is low and leptons are soft.
- $B$ mesons have a relatively long lifetime.
- Travel about $\sim 1$ mm before decaying.
- Decay gives $\sim 4$ charged tracks.
- Look for tracks or vertices displaced from primary vertex.

- Important parameters:
  - Impact parameter resolution: $d/\sigma(d)$.
  - Decay length resolution: $L_{xy}/\sigma(L_{xy})$

- Numerous tagging algorithms have been developed by both experiments.
B tagging

- Example: DØ JLIP algorithm.
- Jet Lifetime Impact Parameter.
- Uses impact parameter significance.
- Tabulate $P_{PV}(d/\sigma(d))$.
  - Probability for track to come from primary vertex, as a function of impact parameter significance.
  - Bin according to $p_T$, number of hits, etc.
- Combine probabilities for all tracks in a jet.
- Typical performance (for jets with good tracks):
  - $\sim 50\%$ tagging efficiency
  - For $\sim 0.5\%$ mistag rate.
• Common element in many Higgs analyses: $h \rightarrow b\bar{b}$.

• Want to be able to reconstruct Higgs mass peak in $m(b\bar{b})$ to discriminate against background.

• $m(b\bar{b})$ is one of the most powerful variables available!

• Dijet mass resolution is important.
  – Improving resolution from 12% to 10% is equivalent to a 20% luminosity difference.

• Right: CDF studies on central jets.

• $\sim 10\%$ seems achievable.
$WH \rightarrow \ell \nu b\bar{b}$ results

Both: Large lepton $p_T$, $E_T$, jet $E_T$. Exactly two jets.

**DØ**

$\ell \equiv$ electrons only  \quad 25 < M_{W_T} < 125 \quad \text{Two } b\text{-tags}

**CDF**

$\ell \equiv e$ or $\mu$  \quad \text{Extra lepton veto}  \quad \text{One } b\text{-tag}

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**DØ Run II Preliminary**  \quad L = 174 pb$^{-1}$

$W + 2$ b-tagged jets, $25 \text{ GeV} < M_T (W) < 125 \text{ GeV}$

Observed  \quad 2

Background  \quad 0.9 \pm 0.4

Expected $WH (m_H=115 \text{ GeV})$  \quad 0.03 \pm 0.1

$\sigma(WH) \times B(H \rightarrow b\bar{b}) < 12.4 \text{ pb} @ 115$

$\sigma(Wbb) < 20.3 \text{ pb}$

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**CDF Run II Preliminary (162 pb$^{-1}$)**

Observed  \quad 62

Background  \quad 60.55 \pm 4.43

Expected $WH (m_H=115 \text{ GeV})$  \quad 0.29

$\sigma(WH) \times B(H \rightarrow b\bar{b}) < 5 \text{ pb} @ 115$
\[(Z \rightarrow ee/\mu\mu)b\] Studies

- Measure the ratio \((Z+b)/(Z+j)\).
  - Study backgrounds for \(ZH\).
  - Probe PDF of \(b\)-quarks.
- Signature:
  - Two isolated, high-\(p_T\) leptons.
  - Dilepton mass near \(m_Z\).
  - Jet \(E_T > 20\) GeV and \(|\eta| < 2.5\).
- Backgrounds estimated from data.
  - QCD fakes and mistags.
- Systematics:
  - \(b\)-tagging efficiency: 16%.
  - Jet energy scale: 10%.
  - Background estimation: 6%.
- Result:
  \[\sigma(Z+b)/\sigma(Z+j) = 0.024 \pm 0.005(\text{stat})^{+0.005}_{-0.004}(\text{syst})\]
- Agrees with NLO calc \(\sim 0.02\) (hep-ph/0312024).
$H \rightarrow WW^*$

- Best mode at the Tevatron for $m_H \gtrsim 140$ GeV.

- Signature:
  - Two isolated, high-$p_T$ leptons.
  - Large $E_T$.
  - Small jet activity.

- Spins of $W$’s are correlated; leptons tend to go in the same direction.
  - Small $m(\ell\ell)$.
  - Small $\Delta\phi(\ell\ell)$.

- Backgrounds:
  - Electroweak $WW$ production.
  - $Z/\gamma \rightarrow \ell\ell$ with mismeasured $E_T$.
  - $W +$ jets with fake lepton.
  - $ZZ, WZ$.

DØ $e\mu$ channel: 158 pb$^{-1}$
After lepton preselection only
$H \rightarrow WW^* \rightarrow ee, e\mu, \mu\mu$

**DØ**
- Channels separate: \( \sim 160 \text{ pb}^{-1} \).
- \( \Delta \phi(ee) < 1.5, \Delta \phi(e\mu/\mu\mu) < 2.0 \).

**CDF**
- Channels combined: \( \sim 184 \text{ pb}^{-1} \).
- \( m(ll) < m_H/2 \).

Fit \( \Delta \phi(ll) \) to get limit.
$H \rightarrow WW^*$ Results

### DØ

|         | ee  | $e\mu$ | $\mu\mu$ |
|---------|-----|--------|--------|
| Observed| 2   | 2      | 5      |
| Expected| $2.7 \pm 0.4$ | $3.1 \pm 0.3$ | $5.3 \pm 0.6$ |

$\sigma \times B(H \rightarrow WW) < 5.7 \text{ pb}$ \hspace{1cm} \leftarrow m_H = 160 \rightarrow$

### CDF

|         | All |
|---------|-----|
| Observed| 3   |
| Expected| $5.8 \pm 0.6$ |

$\sigma \times B(H \rightarrow WW) < 5.6 \text{ pb}$
The branching ratio of $H \to \gamma\gamma$ in the Standard Model is very small.
- $10^{-3} - 10^{-4}$.
- Not feasible for the Tevatron.

Some extensions to the Standard Model predict suppressed coupling of Higgs to various classes of fermions.
- Fermiophobic Higgs (no coupling to any fermions).
- Topcolor (the only fermion the Higgs couples to is the top quark).

With other decay modes suppressed, $H \to \gamma\gamma$ is enhanced.

Mrenna, Wells, PRD63 (2001).
Search for $H \rightarrow \gamma\gamma$

- DØ analysis from $\sim 191$ pb$^{-1}$.
- Require two photons $> 25$ GeV.
  - Isolated EM clusters with no associated tracks.
  - Shower shape cuts.
- $p_T(\gamma\gamma) > 35$ GeV.
- Classify events based on location of photon candidates:
  - CC: Central calorimeter.
  - EC: Endcap calorimeter.
- Data shown on right.
  - Blue: Data
  - Red: Total SM expectation
  - Gray: SM expectation error band
  - Green: QCD background
  - Brown: Drell-Yan $Z/\gamma \rightarrow ee$
  - Black: Direct $\gamma\gamma$.

Higgs Searches at the Tevatron – p. 1
Search for $H \rightarrow \gamma\gamma$: Results

- Use CC-CC and CC-EC events.
- Make final mass window cut in $m(\gamma\gamma)$.
- Varies with $m_H$.
- Width varies:
  - $\sim 6$ GeV for $m_H = 60$.
  - $\sim 10$ GeV for $m_H = 150$.
- Derive 95% limits for fermiophobic and topcolor scenarios.
- Results:
  - Black: Branching ratio limit.
  - Green: One particular model.
  - Magenta: Expected Tevatron exclusion limit for 2 $fb^{-1}$.
MSSM Higgs

- In supersymmetric models, there are five physical Higgs scalars:
  - CP-even: $h$, $H$.
  - CP-odd: $A$.
  - Charged: $H^\pm$.
- Two free parameters:
  - One Higgs mass.
  - $\tan \beta$
- For neutral scalars $\phi \equiv h/H/A$, $b\phi$ coupling is enhanced by $\tan \beta$.
- Look for $\phi b\bar{b}$ production, with $\phi \rightarrow b\bar{b}$.
DØ MSSM Higgs Search

- Data: $\sim 131 \text{ pb}^{-1}$.
- Require at least 3 $b$-tagged jets.
- Jet $E_T$, $|\eta|$ cuts and maximum jets allowed depend on $m_H$.
- At $m_H = 100$:
  - Jet $E_T > 40, > 35, > 15$.
  - $|\eta| < 2.5$.
  - $N_j \leq 4$.
- Backgrounds:
  - QCD light jets.
  - QCD $b\bar{b}j, c\bar{c}j$.
  - $b\bar{b}b\bar{b}$, $(Z \to b\bar{b})j, t\bar{t}$.
- Plot $m(jj)$ for leading two jets and fit to sum of signal and background.
- Set 95% C.L. limit.
Some models predict doubly-charged Higgs bosons: $H^{++}$, $H^{--}$.
- Example: L-R symmetric model.
- Model has parity symmetry at high energies.
- Parity nonconservation appears at low energies via SSB.
- Requires Higgs triplet.

Production at Tevatron via $Z/\gamma^*$:

- Look for like-sign lepton pairs.
  - $ee$, $e\mu$, $\mu\mu$.
- High-$p_T$.
- Isolated.
- Backgrounds:
  - $b\bar{b}$
  - $W + \text{jets}$
  - $Z \to \ell\ell$
  - $WZ$, $WW$
  - $t\bar{t}$

Decays for $m(H^{++})$ likely to be dominantly like-sign lepton pairs.

Branching ratios not well constrained.
Doubly-charged Higgs Results

|       | CDF: 240 pb$^{-1}$ | DØ: 113 pb$^{-1}$ |
|-------|--------------------|-------------------|
|       | Bkg | Data | $m(H_L^{++})$ | $m(H_R^{++})$ | Bkg | Data | $m(H_L^{++})$ | $m(H_R^{++})$ |
| $ee$  | 1.5$^{+0.9}_{-0.6}$ | 0 | > 133 |       |       |       |       |
| $\mu\mu$ | 0.8$^{+0.5}_{-0.4}$ | 0 | > 136 | > 113 | 1.5 $\pm$ 0.4 | 3 | > 118.4 | > 98.2 |
| $e\mu$ | 0.4 $\pm$ 0.2 | 0 | > 115 |       |       |       |       |
Long-term Higgs Sensitivity

- Base projection:
  Exclude 115–130.
  $3\sigma$ evidence up to $\sim 120–125$.

- Design projection:
  $3\sigma$ evidence up to $\sim 130$.
  $5\sigma$ discovery up to $\sim 115–120$.

- Caveat: Study assumed upgrades of vertex detectors (now canceled).

- Accelerator luminosity projections:
  - $\sim 8 \text{ fb}^{-1}$ by end of 2009 for design (challenging) projection.

- Base projection (conservative):
  - Allowing for schedule slippage and underperformance.
  $\sim 4 \text{ fb}^{-1}$ by end of 2009.

Tevatron Higgs Sensitivity Study 2003:
Summary

- Only a couple hundred pb$^{-1}$ analyzed so far.
- About half of what’s been recorded.
- Results so far focused on
  - Understanding detector response.
  - Understanding background processes.
- Tevatron can already set competitive limits for some non-SM processes.
- Tevatron is performing better than predicted for 2004.
- Data will keep accumulating.

- SM Higgs is very challenging to find. But if performance projections hold, we’ll have sensitivity to interesting range of Higgs masses.
References

- CDF results:
  http://www-cdf.fnal.gov/physics/exotic/exotic.html

- DØ results:
  http://www-d0.fnal.gov/Run2Physics/WWW/results/HIGGS/higgs.htm

- 2003 Higgs Sensitivity Study:
  http://www-d0.fnal.gov/Run2Physics/higgs_sensitivity_study.html

- 2000 Higgs Working Group Report:
  hep-ph/0010338