Search for high mass standard model
Higgs boson at Tevatron

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on behalf of the CDF and DØ collaborations
Where to look for SM Higgs boson?

Indirect constraints from EW measurements

\[ M_H < 152 \text{ GeV} \ @95\% \]

Direct constraints from LHC

\[ 122.5 \text{ GeV} < M_H < 127 \text{ GeV} @95\% \]

July 4\textsuperscript{th} : Observation of a Higgs-like particle \( @5\sigma \) by Atlas & CMS around 125 GeV
The Tevatron proton-antiproton collider

Run I (1993-1996)
~120 pb\(^{-1}\) per experiment - top quark discovery

Run II: (2002-2011)

- Shutdown 30 September 2011
- ~12 fb\(^{-1}\) delivered per experiment
- ~9.5 fb\(^{-1}\) for physics analysis

36×36 bunches
396 ns bunch crossing

Most of the Higgs results today rely on the full data set
Higgs production at the Tevatron

Production cross section (for 115< m_H<180 GeV)

- In the 1.2-0.3 pb range for gluon fusion gg → H
- In the 0.2-0.03 pb range for WH associated vector boson production
- In the 0.08-0.03 pb range for the vector boson fusion qq → Hqq
Decay modes depend on the Standard Model Higgs boson mass.

Searches at high mass:
- Look for W decay products
- Peak sensitivity just above threshold $M_H \sim 165$ GeV

Low Mass vs High Mass channels:
comparable sensitivities for 125-130 GeV

$m_H < 135$ GeV

- $H \rightarrow bb$
- $H \rightarrow \tau\tau$

$m_H > 135$ GeV

- $H \rightarrow WW^*$
The different high mass channels

Overwhelming QCD background in hadron colliders:
→ need for lepton and/or missing $E_T$ signature

Searches driven by $H \rightarrow WW$
- Di-lepton of opposite signs (OS) + $E_T$
  Clean signal, Small Br~6% (ee +eμ + μμ)
- Lepton+ tau+ $E_T$
  Small Br~4% (eτ+ μτ)
  Difficulty to reconstruct hadronic taus
- Lepton + $E_T$ + jets
  Larger Br ~ 30% (e+jets, μ+jets)
  Large W+jets background, hard to model

Also $WH \rightarrow WW$, $ZH \rightarrow WW$
- Di-lepton of same sign + $E_T$
  Clean signature, but small $\sigma \times$Br
- Trilepton + $E_T$
  Clean signature, but small $\sigma \times$Br
- Lepton + $E_T$ + 4 jets : challenging

Also $H \rightarrow ZZ$
- 4 leptons are a clean but very rare signature
Backgrounds to Higgs

- **Di-boson WW, WZ, ZZ**
  - Can yield 1, 2, 3 or 4 real leptons
  - NLO calculation for cross-sections
  - WW = irreducible background for $H \rightarrow WW$
  - NLO correction for $p_T$ and di-lepton opening angle

- **Z+jets, Z+γ**
  - Mismeasured jets or leptons yielding $E_T$
  - Jet or gamma faking a 3rd lepton
  - NNLO or data cross-sections, data-based corrections to model $p_T(Z)$

- **W+jets, W+γ**
  - Jet or $γ$ faking lepton for multi-lepton signatures
  - W+jets background to semi-hadronic signatures
  - Data driven correction

- **Top pair**
  - Two real W's from top decays
  - Cross-section normalized at NNLO

- **QCD multijet events**
  - Jets faking leptons
  - Mismeasured jets creating $E_T$
Search Strategy

Start with pre-selection of isolated high $p_T$ leptonic events

Try to maximize acceptance
- Many different lepton reconstruction categories, loose lepton-id
- Lower kinematic requirements
- Inclusive triggers when possible

Split analyses into subchannels
- Different signal/background to maximize discriminating power
- Sensitivity to different signal production mode
- Also gives more handles to control background level and systematic uncertainties

Multivariate techniques to maximize use of available information
- Decision trees (BDT), Neural Networks (NN), Matrix Element (ME)
- Trained for each subchannel and Higgs mass hypothesis.
- Input variables:
  - event topology, lepton kinematics, quality of leptons, jet content, Matrix Element discriminant, relation between lepton and $E_T$, relation between jets and $E_T$, b-tag of events (against top)
- Some analyses employ several MVA trained against different specific backgrounds
Use data as much as possible

- Instrumental background need to be determined on data
  - jets faking leptons, photon faking electrons, charge mismeasurements, Missing $E_T$

- Background enriched samples to tune or check modeling of specific background processes

**DY sample**

**W+γ sample**
Validate methodology using data

e.g. at DØ:

Measure $pp \rightarrow WW \rightarrow l\nu l\nu$ cross-section

- Employ same analysis technique as in searches for $H\rightarrow WW \rightarrow l\nu l\nu$
  - Same subchannels
  - Same inputs to MVA
  - Train MVA to discriminate WW production
  - Similar treatment of systematic uncertainties

$H \rightarrow WW \rightarrow l\nu l\nu$ search with 8.6 fb$^{-1}$ submitted to PRD [arxiv:1207.1041]

\[\begin{array}{|c|c|}
\hline
\text{channel} & \text{result} \\
\hline
\sigma_{WW}^{ee} & 10.6 \pm 0.6 \text{ (stat)} \pm 0.6 \text{ (syst)} \\
\sigma_{WW}^{ee} & 12.4 \pm 1.2 \text{ (stat)} \pm 0.9 \text{ (syst)} \\
\sigma_{WW}^{e\mu} & 11.0 \pm 0.9 \text{ (stat)} \pm 0.7 \text{ (syst)} \\
\sigma_{WW}^{\text{combined}} & 11.1 \pm 0.5 \text{ (stat)} \pm 0.6 \text{ (syst)} \\
\sigma_{WW}^{NLO} & 11.7 \pm 0.7 \\
\hline
\text{source: Campbell and Ellis, PRD 60, 113006 (1999)}
\end{array}\]

Measured cross-section: $11.1 \pm 0.8$ pb
in agreement with NNLO prediction
Same sign di-lepton + $E_T$ channels

Limit derived from MVA distribution

sensitivity @125 GeV

CDF ~12x $\sigma_{SM}$  
DØ ~12x $\sigma_{SM}$
Tri-lepton channels

Signature: 3 isolated high $p_T$ leptons, Large missing $E_T$

- Split into: non-Z, $Z+1$ jet, $Z+2$ jet channels @CDF
- Split into: non-Z, $Z+MET_{\text{sig}}>2$, $Z+MET_{\text{sig}}<2$ @DØ $\mu\mu e$

Limits derived from MVA distribution

sensitivity @125 GeV

<table>
<thead>
<tr>
<th>CDF</th>
<th>DØ</th>
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<tbody>
<tr>
<td>$\sim 13 \times \sigma_{\text{SM}}$</td>
<td>$\sim 11 \times \sigma_{\text{SM}}$</td>
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</tbody>
</table>
4 leptons @CDF

Rare signature because of small Branching ratios. Larger non resonant ZZ production as main background

- Eg for $M_H=130$ GeV :
  - Expect 0.2 signal vs 11 bkg events
    0.1 from $H \rightarrow ZZ \rightarrow l\,l\,l\,l$
    0.1 from $ZH \rightarrow ZWW \rightarrow l\,l\,l\,l\,\nu\,\nu$, $ZH \rightarrow l\,l\,\tau\,\tau$

![Graph showing event distribution for 4 leptons at CDF](image)

<table>
<thead>
<tr>
<th>Higgs Mass (GeV/c^2)</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
<th>220</th>
<th>240</th>
<th>260</th>
<th>280</th>
<th>300</th>
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<tbody>
<tr>
<td>σ_{SM} (σ_{SM})</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>1</strong></td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>@125 GeV</th>
<th>@145 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>~30 x $\sigma_{SM}$</td>
<td>~10 x $\sigma_{SM}$</td>
<td></td>
</tr>
</tbody>
</table>
Challenging analyses with large W+jets background

$H \rightarrow WW \rightarrow l\nu jj$ and $VH \rightarrow VWW \rightarrow l\nu jjjj$

- W mass constraint to reconstruct neutrino $p_z$
- Full reconstruction of the kinematic
- Enhance sensitivity for $M_H > 160$ GeV

New in 2012

$VH \rightarrow VWW \rightarrow l\nu jjjj$

- Part of the “low mass” $WH \rightarrow l\nu bb$ analysis
- 4-jet bin (0 and 1 tag) sensitive to high mass Higgs

Limits derived from MVA distribution

$\sim 25 \times \sigma_{SM}$ $\sim 80 \times \sigma_{SM}$
Opposite Sign Signature:
- 2 isolated high $p_T$ leptons, opposite signs
  - Unlike $W$+jets and QCD background
- Large missing $E_T$
  - Unlike Drell-Yan background
- Higgs is scalar at rest + V-A interaction
  - The leptons tend to be collinear
  - Small $\Delta\phi(l,l)$
  - Unlike WW background
OS di-lepton + $E_T$ selection

Get rid of the dominant Z/$\gamma$ background.

- Use kinematics, in particular $E_T$ based variables that ensure $E_T$ is significant and not due to mismeasured object
- DØ (ee, $\mu\mu$) employs Decision Trees trained against Z/$\gamma$

Typically: - O(1000) events remains at this stage for each sub-selection
- S/B is of order O(1/100)
Get rid of the dominant $Z/\gamma$ background.

- Use kinematics, in particular $E_T$ based variables that ensure $E_T$ is significant and not due to mismeasured object
- DØ (ee, $\mu\mu$) employs Decision Trees trained against $Z/\gamma$

Typically: - $O(1000)$ events remains at this stage for each sub-selection
- $S/B$ is of order $O(1/100)$
**Di-lepton + $E_T^{(OS)}$ : subchannels**

Split according to jet multiplicity (CDF+DØ)

- Better sensitivity to H+jets final states: qqH, WH, and ZH
  - important for lower masses
- Each multiplicity bin correspond to a different dominant background
  - 0 jet: WW
  - 1 jet: WW + Z/γ
  - ≥2 jets: top pairs

[Graphs and histograms showing event distribution for different jet multiplicities and Higgs mass $m_H=160$ GeV.]
**Di-lepton + $\mathbb{E}_T$ Subchannels**

Split analysis according to:

- Lepton flavor: $e\bar{e}, e\mu, \mu\mu$ (DØ)
- Signal purity based on lepton quality (CDF)
- Low (<16 GeV) di-lepton mass (CDF)

**Enriched/Depleted WW samples thanks to a dedicated WW-BDT discriminant (DØ ee, $\mu\mu$)**

- Different instrumental (fake) background
- Different background composition
- Different lepton momentum resolution
  - typically 4% for electrons, 10% for muons at D0

![Graph showing di-lepton + $\mathbb{E}_T$ Subchannels](image)

**New in 2012**

Higgs Hunting 2012, Orsay

B. Tuchming - SM High Mass Higgs at Tevatron
OS di-lepton channels: multivariate analysis

MVA outputs are inputs for statistical analysis of data

0 jet high S/B

2 jets

+ many others ...

No excess above background → derive limits
Both experiments achieve Higgs sensitivity with this channel only.
Systematic uncertainties

Uncertainties have a sizable impact

- **Flat:** affect overall normalization
- **Shape:** modify output of final discriminant
- **Have to account of correlations among channels and experiments**
- **Impact is reduced thanks to constraints from background dominated region**
- **Degrade sensitivity by ~15-25%**

<table>
<thead>
<tr>
<th>Main systematics</th>
<th>Signal</th>
<th>Bkg</th>
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</thead>
<tbody>
<tr>
<td>Lepton id +trigger</td>
<td>2-5%</td>
<td>2-5%</td>
</tr>
<tr>
<td>Lepton/jet fakes</td>
<td>-</td>
<td>14-50%</td>
</tr>
<tr>
<td>charge mis-id</td>
<td></td>
<td>20-40%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>5.9%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Jet calibration</td>
<td>5-17%</td>
<td>3-30%</td>
</tr>
<tr>
<td>$E_T$ modeling</td>
<td></td>
<td>~20%</td>
</tr>
<tr>
<td>$p_T(Z) \ p_T(W)$ $p_T(WW)p_T(H)$</td>
<td>1.5%</td>
<td>1-5%</td>
</tr>
<tr>
<td>Cross-sections</td>
<td>(VBF,VH) 5-10%</td>
<td>6-10%</td>
</tr>
<tr>
<td>$gg \rightarrow H$ production</td>
<td>(jet dependent) 7-33%</td>
<td>-</td>
</tr>
<tr>
<td>Scale</td>
<td></td>
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<tr>
<td>PDF</td>
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</tbody>
</table>

$m_H=165$ GeV

![Graph showing Tevatron Run II Preliminary Data-Background, SM Higgs Signal, and ±1 s.d. on Background with $m_H=165$ GeV]
Results from both experiments

Each experiment alone is sensitive to sizable mass range ~165 GeV

For low masses [120-140] GeV: results from DØ show some slight excess

A Higgs particle of 125 GeV, would create on average a ~1σ excess around [120-150] GeV
CDF and DØ first achieved combined sensitivity to high mass Higgs in 2008

Since then:
- More data
- More channels
- Continuous improvements in analysis techniques
- Still room for a few more improvements before final publication

Each experiment is now probing @95% CL a sizable mass range of ~[155,175] GeV

@125 GeV
- Individual exclusion sensitivity is around 3.2 x SM
- CDF+DØ results are not inconsistent with a Higgs of 125 GeV
  - No Large deviation relative to background-only hypothesis
  - DØ alone sees 1 to 1.5 sigma excess in the range [120-150] GeV

Stay tuned:
- See next talks for the contributions of low mass channels
- See next talk for the combined CDF/DØ results

More details:
- CDF: http://www-cdf.fnal.gov/physics/new/hdg/Results.html
- DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
**DØ and CDF limits**

### DØ \( H \to WW \)

<table>
<thead>
<tr>
<th>( m_H )</th>
<th>115</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>145</th>
<th>150</th>
<th>155</th>
<th>160</th>
<th>165</th>
<th>170</th>
<th>175</th>
<th>180</th>
<th>185</th>
<th>190</th>
<th>195</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected:</td>
<td>5.81</td>
<td>4.37</td>
<td>3.20</td>
<td>2.57</td>
<td>2.09</td>
<td>1.81</td>
<td>1.54</td>
<td>1.31</td>
<td>1.10</td>
<td>0.79</td>
<td>0.72</td>
<td>0.91</td>
<td>1.07</td>
<td>1.32</td>
<td>1.68</td>
<td>2.05</td>
<td>2.43</td>
<td>2.80</td>
</tr>
<tr>
<td>Observed:</td>
<td>10.59</td>
<td>5.87</td>
<td>4.59</td>
<td>3.18</td>
<td>3.42</td>
<td>2.76</td>
<td>1.89</td>
<td>1.63</td>
<td>1.41</td>
<td>0.80</td>
<td>0.74</td>
<td>0.99</td>
<td>1.60</td>
<td>1.35</td>
<td>1.87</td>
<td>2.37</td>
<td>3.02</td>
<td>3.98</td>
</tr>
</tbody>
</table>

### CDF \( H \to WW \)

| High Mass | 110 | 115 | 120 | 125 | 130 | 135 | 140 | 145 | 150 | 155 | 160 | 165 | 170 | 175 | 180 | 185 | 190 | 195 | 200 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(-2\sigma/\sigma_{SM}\) | 5.39| 2.95| 1.88| 1.29| 0.96| 0.74| 0.64| 0.52| 0.46| 0.40| 0.32| 0.30| 0.34| 0.42| 0.47| 0.58| 0.75| 0.86| 1.00|
| \(-1\sigma/\sigma_{SM}\) | 8.61| 4.71| 2.97| 2.05| 1.52| 1.22| 1.01| 0.86| 0.74| 0.64| 0.48| 0.46| 0.54| 0.65| 0.75| 0.96| 1.18| 1.40| 1.59|
| Median/\sigma_{SM}\) | 13.06| 7.07| 4.47| 3.08| 2.29| 1.85| 1.53| 1.31| 1.13| 0.96| 0.71| 0.69| 0.81| 0.97| 1.13| 1.46| 1.80| 2.10| 2.42|
| \(+1\sigma/\sigma_{SM}\) | 19.03| 10.25| 6.51| 4.49| 3.34| 2.67| 2.24| 1.91| 1.66| 1.41| 1.03| 0.99| 1.19| 1.41| 1.65| 2.15| 2.63| 3.10| 3.57|
| \(+2\sigma/\sigma_{SM}\) | 26.57| 14.32| 9.21| 6.28| 4.62| 3.75| 3.17| 2.69| 2.32| 1.97| 1.43| 1.39| 1.65| 1.95| 2.31| 2.99| 3.71| 4.30| 4.99|
| Observed/\sigma_{SM}\) | 17.28| 11.52| 4.96| 2.98| 2.81| 1.85| 1.84| 1.22| 0.94| 0.83| 0.50| 0.40| 0.84| 0.99| 1.26| 1.87| 2.56| 5.10| 5.33|
Higgs search within 4th generation model

- New heavy generation of quarks
  - $ggH$ coupling is multiplied by 3 compared to SM
  - Production is enhanced by 9
- Search in di-lepton +MET channel can be recycled
  - Some analysis tuning required because of extended mass reach (eg $\Delta \phi(l,l)$ cut not applicable when W's are boosted)

CDF only 8.2 fb$^{-1}$ (summer 11) $123 < m_H < 215$ GeV @95%CL
DØ only 8.1 fb$^{-1}$ (summer 11) $140 < m_H < 240$ GeV @95%CL
Combined result (summer 11) $124 < m_H < 286$ GeV @95%CL
DØ OS subchannels

(a) $\pi + \not{E}_T$

(b) $e\mu + \not{E}_T$

(c) $ee + \not{E}_T$

(d) $\mu \mu + \not{E}_T$
Slight $[1\sigma -1.5\sigma]$ excess at low mass
Higgs Hunting 2012, Orsay

B. Tuchming - SM High Mass Higgs at Tevatron

H → WW CDF subchannels

OS 0jet

OS 1jet

OS 2jets

low M(lep,lep)
Di-lepton channels: new in 2012

CDF
- More data, typically 20%

DØ
- More Data, typically 20%
- Opposite sign channels: \(ee, \mu\mu\)
  - Improved electron ID
  - Split into enriched/depleted WW background region
  - \(O(10\%)\) improvement
- New Tri-lepton analyses
  - Split into three regions: non Z, Z+MET, Z+low MET, for \(\mu\mu\)
**Tevatron Experiments at RunII**

- **New**
  - silicon detector
  - Drift chamber
  - TOF PID system

- **Upgraded**
  - Calorimeter
  - DAQ/trigger
  - displaced-vertex trigger

- **New**
  - Tracking in B-field
  - Silicon detector
  - fiber tracker

- **Upgraded**
  - Calorimeter, muon system
  - DAQ/trigger
  - RunIIb: Silicon layer 0, Cal Trigger
Recent LHC results

- Summer 11: LHC started to exclude a large range at high mass
- Winter 12: Remaining allowed region became narrower
  - Hints of an excess around 125 GeV
- July 4th 2012, updated results:
  - Searches exclude a large mass range up to 600 GeV
  - Only allowed region around 125 GeV
  - Observation of a Higgs-like particles @5 sigma claimed by Atlas & CMS around 125 GeV
**gg → H (μᵣ, μᵢ) scale uncertainties**

- Vary independently ggH +0jet, ggH+1jet, ggH+2jets scale uncertainties (s0, s1, s2).
- Account for migration between jet multiplicity bin.

<table>
<thead>
<tr>
<th></th>
<th>s0</th>
<th>s1</th>
<th>s2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 jet</td>
<td>0.134</td>
<td>-0.230</td>
<td>0.0</td>
</tr>
<tr>
<td>1 jet</td>
<td>0.0</td>
<td>0.35</td>
<td>-0.127</td>
</tr>
<tr>
<td>2+jet</td>
<td>0.0</td>
<td>0.0</td>
<td>0.33</td>
</tr>
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</table>