Tevatron Results on Higgs and $m_W$

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J.Hopkins workshop, 17/10/2012
CDF and D0 data

- Tevatron 12 fb$^{-1}$ delivered, up to Sep. 2011
- Collected 10 fb$^{-1}$/experiment
- Analyses still ongoing
Overview of Tevatron Higgs analyses

- In the full Tevatron sample:
  - Expect <200 Higgs events
  - With a background of ~200K
  - Partitioned over many final states
- CDF and D0 analyses: ~90 orthogonal sub-channels each
- Most important >150 GeV
  - WWW, WWZ, WW, ZZ, τ-decays, full/semi-leptonic...
- Most important <150 GeV
  - WH, ZH, METbb, ttH, γγ, VBF→bbjj

- Had m(H) been >150 GeV, discovery would have been easier…
  - Large yields at both Tev at LHC
- …but 125 GeV allows more interesting studies after discovery
  - Can study fermion couplings
  - Complementarity TeV-LHC
Milestone Higgs paper from CDF+D0, was based on “high-mass” Higgs search.

In Feb. 2010 the limit curve touched 1.0 for the first time giving the start to the Higgs program:

Excluded $M_H$ in [163-166] GeV

Progress has been fast since then.

I will concentrate on the 125 GeV Higgs for the rest of the talk.
Producing the SM Higgs at different hadron colliders

“gluon fusion” (via fermion loop)

“Higgs-strahlung” (radiated by a VB)

Relatively more important at Tevatron (22% of gg)

VB-fusion
Tevatron and the $\gamma\gamma$ mode

- Search performed with mass fit
- Addition of NN
- Latest improvement by DZero
Tevatron combined $\gamma\gamma$ limits

- Expected limit @125GeV = 6.3 * SM - observed ~10*SM
**Fermiophobic limits**

CDF Run II Preliminary

\[ \mathbf{H} \rightarrow \gamma \gamma \text{ only} \]

CDF \( M(h_f) > 114 \text{ GeV/c}^2 \)

Tevatron Run II Preliminary \( L \leq 8.2 \text{ fb}^{-1} \)

\[ \mathbf{H} \rightarrow \gamma \gamma, WW \]

CDF \( M(h_f) > 119 \text{ GeV/c}^2 \)

Tevatron combined:

\[ M(h_f) > 119 \text{ GeV/c}^2 \]

\( \gamma \gamma \) information from Tevatron essentially superseded by LHC

[arXiv:1109.0576 [hep-ex]]

August 9, 2011
Four channels cover 90% of the 125GeV Higgs yield for at the Tevatron
- Their total yield is ~constant in the low-mass range - but composition changes
- The WW channel is the only one not requiring associate production - still:
  - 30% of the WW final state comes from associate production
  - WWW and ZWW channels have better S/B than gg->H
# $H \to WW$ Search Channels @Tevatron

<table>
<thead>
<tr>
<th>Channel</th>
<th>Main Signal</th>
<th>Main Background</th>
<th>Most Important kinematic variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS dileptons, 0 Jets</td>
<td>gg→H</td>
<td>WW</td>
<td>LR$<em>{HWW}$, ΔR$</em>{ll}$, $H_T$</td>
</tr>
<tr>
<td>OS dileptons, 1 Jet</td>
<td>gg→H</td>
<td>DY</td>
<td>ΔR$_{ll}$, $m_T(ll,E_T)$, $E_T$</td>
</tr>
<tr>
<td>OS dileptons, 2+ Jets</td>
<td>Mixture</td>
<td>t-tbar</td>
<td>$H_T$, ΔR$<em>{ll}$, $M</em>{ll}$</td>
</tr>
<tr>
<td>OS dileptons, low $M_{ll}$, 0 or 1 Jet</td>
<td>gg→H</td>
<td>W+γ</td>
<td>$p_T(l2)$, $p_T(l1)$, $E(l1)$</td>
</tr>
<tr>
<td>SS dileptons, 1+ Jet</td>
<td>WH→WWW</td>
<td>W+Jets</td>
<td>$E_T$, $\sum E_T$, $M_{ll}$</td>
</tr>
<tr>
<td>Tri-leptons, no Z candidate</td>
<td>WH→WWW</td>
<td>WZ</td>
<td>$E_T$, ΔR$_{ll}$, Type(III)</td>
</tr>
<tr>
<td>Tri-leptons, Z candidate, 1 Jet</td>
<td>ZH→ZWW</td>
<td>WZ</td>
<td>Jet $E_T$, ΔR$_{ll}$, $E_T$</td>
</tr>
<tr>
<td>Tri-leptons, Z candidate, 2+ Jets</td>
<td>ZH→ZWW</td>
<td>Z+Jets</td>
<td>$M_{ll}$, $M_H$, ΔR$_{WW}$</td>
</tr>
<tr>
<td>OS dilepton, electron + hadronic tau</td>
<td>gg→H</td>
<td>W+Jets</td>
<td>ΔR$_{ll}$, τ id variables</td>
</tr>
<tr>
<td>OS dilepton, muon + hadronic tau</td>
<td>gg→H</td>
<td>W+Jets</td>
<td>ΔR$_{ll}$, τ id variables</td>
</tr>
</tbody>
</table>

**Breakdown by #jets**

**Associated production**

$W \to \tau \nu$
Comparision of SS /OS dilepton searches

CDF Run II Preliminary

OS 0 Jets, High S/B
$M_H = 125 \text{ GeV/c}^2$

Events / 0.05

NN Output
Divide-and-conquer approach

- Separating events into multiple analysis channels and combining the results improves sensitivity.
- Allows to use separate, optimized discriminates for each channel based on:
  - specific signal contributions
  - specific background contributions
  - specific event kinematics
- Then combine everything in a single histogram, binning in S/B (Likelihood ratio).
• WW still gives the largest contribution to the Tev-excluded range: 147-180 GeV
• Sensitivity @125 ~2*SM - No significant signal (~1σ deviation)
Comparisison of SS /OS dilepton searches

CDF Run II Preliminary

SS 1+j

Higgs Mass (GeV)

95% C.L./σ_{SM}

OS 0j

Higgs Mass (GeV)

95% C.L./σ_{SM}

Standard Model

SS 1+ Jets Expected
SS 1+ Jets ± 1σ
SS 1+ Jets ± 2σ
SS 1+ Jets Observed

OS 0 Jets ± 1σ
OS 0 Jets ± 2σ
OS 0 Jets Observed
Reconstruction of VH channels

ZH → ννbb
Hard background

WH → lνbb
Largest yield

ZH → llbb
Cleanest

Select:
- 0, 1, 2 leptons and/or missing E_t
- Two high E_t jets

Critical points:
- Lepton reconstruction and selection efficiencies
- Efficiency for tagging b-quark jets
- Dijet mass resolution
B-tagger calibration

- Both CDF and D0 employ sophisticated MVA algorithms (NN/BDT) with b-jet efficiencies of up to 60-80%, and u,d,s,g-jet mis-ID rates ($\lesssim 1-10\%$)
- Tested in two real data samples:
  - $tt$-enhanced samples (simultaneously extract $tt$ cross section & tagger performance corrections)
  - Jet pairs with one jet containing an electron (either conversion or from heavy flavor decay)
Mass Resolution for b-jets

- Bottom quark jets have properties which are different from standard light flavor quark jets
- Specialized jet energy scale corrections focused on bottom quark jets improve our dijet invariant mass and missing transverse energy measurements
Specialized Jet Energy algorithm for b-jets

- Neural network correlates all jet-related variables and returns most probable jet energy based on bottom quark hypothesis – better signal/background separation

CDF II Preliminary

- Standard corrections
- b-targeted corrections

CDF II Preliminary

- Signal mass resolution
Combining all discriminants
Tevatron Combined $H \rightarrow b\bar{b}$-bbar Discriminant

Tevatron Run II $H \rightarrow b\bar{b}$, $L \leq 9.7$ fb$^{-1}$

- Data-background
- SM Higgs signal, $m_H=125$ GeV/c$^2$
- $\pm 1$ s.d. on background

log$_{10}$(s/b)
From Discriminants to Limits

• Combined binned likelihood function

\[ L(R, \hat{s}, \hat{b}|\vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{n_{ij} e^{-\mu_{ij}}}{\mu_{ij}^{n_{ij}}} \]

• Incorporate sistematics as nuisance parameters
  – About 20% effects

• Uncertainties taken on both the shapes and normalizations of signal & background templates

• Additional constraints on background model obtained directly from fit
**Tevatron b-bbar limits and significance**

- Local p-value distribution for background-only expectation.
- Minimum Local p-value: $3.3 \sigma$ (at $m=135\text{GeV}$)
- Global p-value (LEE=2): $3.1\sigma$

*We interpret these results as evidence for the presence of a new particle, produced in association with a weak vector boson and decaying to a bottom-antibottom quark pair* [Phys. Rev. Lett. 109, 071804 (2012)]

- Local p-value@125: $2.8 \sigma$ (no LEE needed)
Tevatron's b-bbar signal rate

- Cannot determine mass precisely, but shape of the excess quite similar to expectation from SM Higgs at 125 GeV
- The amplitude of the excess appears slightly larger.
- Cross section estimate:
  \[(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow b \bar{b}) = 0.23^{+0.09}_{-0.08} \text{ pb} \text{ (insensitive to mass)}\]
- Compare to SM expectation@125 GeV
  \[0.12 \pm 0.01 \text{ pb}\]

The signal is compatible (1σ) with a SM Higgs @125 GeV
**H->bb, straight mass view**

- Simple overlay of $H\to bb$ signal prediction for the dijet invariant mass ($MH = 120 \text{ GeV}$)
  - Data and diboson prediction from Tevatron low-mass WZ/ZZ measurement (important cross-check !)
  - Additional signal statistically compatible
Individual experiments results in $b\bar{b}$

CDF Limits $m_H = 125$ GeV
- Observed: $4 \times \sigma_{SM}$
- Expected: $1.6 \times \sigma_{SM}$

D0 Limits $m_H = 125$ GeV
- Observed: $3 \times \sigma_{SM}$
- Expected: $2 \times \sigma_{SM}$
Comparing different Higgs modes

All modes compatible with SM Higgs scenario within errors
All channels combined

CDF Run II Preliminary, $L \leq 10$ fb$^{-1}$

DØ Preliminary, $L_{\text{int}} \leq 9.7$ fb$^{-1}$

SM Higgs Combination

95% CL Limit on $\sigma / \sigma_{\text{SM}}$

Higgs Boson Mass (GeV/c$^2$)

Tevatron Run II Preliminary, $L \leq 10$ fb$^{-1}$

ATLAS+CMS Exclusion

February 27, 2012
Full-combination p-values

- Minimum Local p-value: 3.0 $\sigma$ (at m=120GeV)
- Global p-value (LEE=4): 2.5$\sigma$
- Local p-value@125 (no LEE): 2.8 $\sigma$

[arXiv:1207.0449 [hep-ex]]

Minimum p-value corresponds to SM-predicted rates
Tevatron in the Higgs coupling game

- After the Higgs mass has been measured, the question is the couplings.
- Above is an example of fit produced just after spring results (based on just limit information).
- Tevatron giving some important inputs. Dominates b-bbar information.

Giardino et al. [1203.4254]
Anything more on the Higgs?

• Most of the improvements to the analyses happened recently - latest results ~20% better on the same sample
• The history has been one of continuing improvements - there may still be some additional gain to be made.

• A personal favorite: constraining the invisible Higgs width
  – This may be possible at the Tevatron in the ZH -> ll + MET
  – Both D0 and CDF have reconstructed ZZ-> ll + νν
    [CDF 6fb-1: PRL 108, 101801 (2012) ]
  – σ*BR(ZZ-> ll νν) ~ 240fb, while σ(ZH) is ~ 80fb
    might be within the sensitivity of a specifically optimized analysis.
What else can we do to understand the Fermi scale?
What else can we do to understand the Fermi scale?

• We live in a different era of physics than few months ago.

• No direct evidence for new physics at LHC

• Finding the Higgs (candidate) mass has turned attention from “Higgs search” to “Higgs couplings”.
  – Hoping to find out what else is there, if any
  – Will keep us busy for a while.

• There is also another interesting shift of perspective
Impact of $m_H$ on EWK tests

- We have been using **EWK data** to predict the **Higgs mass**.
  - Tevatron’s $M_{t\bar{t}}$, $m_W$ crucial inputs
  - Dependence on log($m_H$) required high precision to estimate $m_H$ precisely
    $$M_H = 94^{+25}_{-22} \text{GeV},$$

- Today, use the **Higgs mass** to predict the **W boson mass**.
  - Dependence on log($m_H$) means:
    from $m_H$ we can predict $m_W$ precisely
  - Previous SM prediction of $m_W$: $\sigma = 28 \text{ MeV}$

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta \alpha_{\text{had}}} \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\text{theo}},$$

= $80.359 \pm 0.011_{\text{tot}},$

(or in quadrature: $0.008$)

Possible non-SM contributions to $m_W$

- $m_W$ can be expressed as:
  $$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W} \left(1 - \Delta r\right)$$

- Where radiative corrections $\Delta r = \Delta r(SM) + \Delta r(NP)$, where $\Delta r(NP)$ could come from many non-SM processes:
  - Generic new fermions/sfermions
  - Generic gauge bosons
  - New Higgs/Goldstone bosons
  - Chargino/Neutralino/Higgsino, and others...

After knowing $m_H$, $m_W$ is much more sensitive to detect $\Delta r(NP) \neq 0$
MW experimental status few months ago

- Best measurements from Tevatron:
  - DØ \( M_W = 80401 \pm 43 \) MeV [1 fb\(^{-1}\), e]
  - CDF \( M_W = 80413 \pm 48 \) MeV [200 pb\(^{-1}\), e+\(\mu\)]

- WA: \( \sigma_{\text{exp}} = 23 \) MeV
- Little motivation to improve it when \( \sigma_{\text{th}} \) was 28 MeV
- NB Mtop is known well enough already (impact \( \sim 5 \) Mev)

The recent Tevatron measurement of \( m_W \) is particularly timely, bringing the WA experimental resolution down.
Factors affecting mW measurement

- INITIAL STATE RADIATION (aka RECOIL)
  - BOTH QCD AND QED
  - TO PT(W) → 0

- PILEUP/UE

- FINAL STATE QED

- MOMENTUM SCALE

- PDFs

- Not just statistics: CDF 0.2 → 2.2fb-1 DZero 1.0 → 4.3fb-1
- Each physics factor must be modeled to better than ~5 MeV
- Similarly for detector response
How to achieve high precision

- Start with clean, low-background events
  - i.e., no taus, no hadronic decays
- Lepton pT carries most information
  - Precision achieved: 0.01%
- Hadronic recoil affects inference of neutrino energy
  - Calibrate to ~0.5%
  - Can reduce impact by requiring $p_T(W) \ll M_W$
- Need:
  - Accurate theoretical model
    - Including boson pT model and QED radiation
  - Tunable fast simulation
    - Parameterized detector description for study of systematic effects
  - Large data samples of well-measured states
    - Various dimuon resonances
    - Z boson
Energy scale calibration

CDF

$J/\psi \rightarrow \mu \mu$
$
\gamma \rightarrow \mu \mu$
$Z \rightarrow \mu \mu$

Muon Scale

CDF

$W \rightarrow ev$
$E/p$

Electron Scale

CDF

$Z \rightarrow ee$

Cross Check

Dzero effectively measures mW/mZ
Muon Z mass and track momentum scale

• Perform independent measurement of Z mass using tuned momentum scale
  - \( M_Z = 91180 \pm 12_{\text{stat}} \pm 9_{\text{p-scale}} \pm 5_{\text{QED}} \pm 2_{\text{alignment}} = 91180 \pm 16 \, \text{MeV} \)
  - Excellent agreement with LEP average (91188 \pm 2 \, \text{MeV})
• Add Z data as final calibration point for momentum scale
  - \( \Delta \frac{p}{p_{\text{final}}} = (-1.29 \pm 0.07_{\text{stat}} \pm 0.05_{\text{QED}} \pm 0.02_{\text{align}}) \times 10^{-3} \)
  - Apply scale to W muons and \( E/p \) calibration
  - Systematic uncertainty \( \Delta M_W = 7 \, \text{MeV} \)
Electron Z mass (Dzero)

- Tuned to PDG by construction
- Yields scale uncertainty of 17 MeV
Recoil model validation

- Test recoil model with W events
  - Compare measured recoil in data to model tuned with Z

Recoil projection perpendicular to lepton

Recoil projection in direction of lepton
Transverse mass distributions

CDF (muons)

\[ M_W = (80379 \pm 16_{\text{stat}}) \text{ MeV} \]

\[ \chi^2/\text{dof} = 58/48 \]

CDF (e⁻)

\[ M_W = (80408 \pm 19_{\text{stat}}) \text{ MeV} \]

\[ \chi^2/\text{dof} = 52/48 \]

D0, 4.3 fb⁻¹

\[ \chi^2/\text{dof} = 37.4/49 \]
Multiple consistency checks

- Multiple measurements methods allow several internal checks.
- D0 has 3, CDF has 6
- Performed **blind**: unknown overall shift until the final results is approved.
- Data turn out to be statistically consistent
- Combined with BLUE procedure to yield final result

![CDF II Preliminary](image)

\[ \int L \, dt = 2.2 \text{ fb}^{-1} \]

- **Muons**: $p_T^\gamma$
  - $80406 \pm 22$
- **Muons**: $p_T^l$
  - $80348 \pm 18$
- **Muons**: $m_T$
  - $80379 \pm 16$
- **Electrons**: $p_T^\gamma$
  - $80431 \pm 25$
- **Electrons**: $p_T^l$
  - $80393 \pm 21$
- **Electrons**: $m_T$
  - $80408 \pm 19$
Summary of uncertainties

- Successfully reduced many sources of uncertainty

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>D0</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton energy scale/resn/modelling</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>Hadronic recoil energy scale and resolution</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Parton distributions</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>QED radiation</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>$p_T(W)$ model</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>W-boson statistics</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>26 MeV</td>
<td>19 MeV</td>
</tr>
</tbody>
</table>

- Largely stat. in origin: 10 MeV
- Largely theory in origin: 12 MeV
Final Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0 I</td>
<td>80483 ± 84</td>
</tr>
<tr>
<td>CDF I</td>
<td>80433 ± 79</td>
</tr>
<tr>
<td>DELPHI</td>
<td>80336 ± 67</td>
</tr>
<tr>
<td>L3</td>
<td>80270 ± 55</td>
</tr>
<tr>
<td>OPAL</td>
<td>80416 ± 53</td>
</tr>
<tr>
<td>ALEPH</td>
<td>80440 ± 51</td>
</tr>
<tr>
<td>D0 II (PRL 108, 151804)</td>
<td>80375 ± 23</td>
</tr>
<tr>
<td>CDF II (PRL 108, 151803)</td>
<td>80387 ± 19</td>
</tr>
<tr>
<td>World Average</td>
<td>80385 ± 15</td>
</tr>
</tbody>
</table>
m_W, m_t, m_H

68% and 95% CL fit contours w/o m_W and m_t measurements

68% and 95% CL fit contours w/o m_W, m_t and m_H measurements

M_W world average ± 1σ

m_t Tevatron average ± 1σ
\[ \Delta m(W) = 0.026 \pm 0.017 \text{ GeV} \]

• Any new physics effect must be compatible with this result (now tighter by a factor of 2 !)
Example of new physics sensitivity

\[ M_W \text{ [GeV]} \]

\[ M_{\tau_i} \text{ [GeV]} \]

- Large sneutrino mass splittings, light scalars
- Small sneutrino mass splittings, heavy scalars

\[ m_{\tau_1} < m_{\tau_2} \]

\[ m_{\tau_1, \tau_2} / m_{\tau_1, \tau_2} > 2.5 \]

MSSM

\[ M_W^{\exp} = 80.404 \pm 0.030 \text{ GeV} \]

[JHEP 0608:052, 2006]
Could you do even better?

- D0 has 2x data, CDF 4x
- Managed to reduce most uncertainties by $\sim\sqrt{L}$
  - most notably CDF: 10x jump
- Will need new ideas for Pt(W), QED, and PDFs (new external constraints?)
- Work has already started towards a 10fb-1 analysis: aiming at 10MeV resolution
Conclusion

• Tevatron found evidence for production of a state compatible with SM Higgs and decaying into b pairs
• This and other measurements support the idea that the boson is a SM boson and provide info for couplings
• The measurements of the Higgs mass has increased sensitivity of mW in probing NP effects
• The latest mW from the Tevatron has strongly improved the precision and it is now 2x constraining

• Further digging into Tev data may still yield some valuable physics output on Higgs couplings, and precision EWK

• Thank you for your attention !