From Collisions to Publication

A Higgs Story

Vadim Rusu

- What we have
- What we want
- What can we use
- How do we get it
- How far along are we
**Terra Firma**

- **Standard Model of Particle Physics**
  - 3 generations of fermions
  - Leptons and quarks
  - Force carriers
    - EWK – gamma, W, Z
    - Strong – gluons
  - Very good fit to the experimental data so far

| Measurement                  | Fit     | $|O_{\text{meas}} - O_{\text{fit}}|/\sigma_{\text{meas}}$ |
|-----------------------------|---------|--------------------------|
| $\Delta c_{\text{had}}(m_Z)$ | 0.02758 ± 0.00035 | 0.02766                  |
| $m_Z \, [\text{GeV}]$       | 91.1875 ± 0.0021 | 91.1874                  |
| $\Gamma_Z \, [\text{GeV}]$  | 2.4952 ± 0.0023 | 2.4957                   |
| $\sigma_{\text{had}} \, [\text{nb}]$ | 41.540 ± 0.037 | 41.477                   |
| $R_b$                       | 20.767 ± 0.025 | 20.744                   |
| $A_{t,b}^{0,1}$             | 0.01714 ± 0.00095 | 0.01640                  |
| $A_t(P_{t})$                | 0.1465 ± 0.0032 | 0.1479                   |
| $R_c$                       | 0.21629 ± 0.00066 | 0.21585                  |
| $A_{t,b}^{0,1}$             | 0.1721 ± 0.0030 | 0.1722                   |
| $A_{t,b}$                   | 0.0992 ± 0.0016 | 0.1037                   |
| $A_{t,b}^{0,1}$             | 0.0707 ± 0.0035 | 0.0741                   |
| $A_t$                       | 0.923 ± 0.020 | 0.935                    |
| $A_c$                       | 0.670 ± 0.027 | 0.668                    |
| $A_t(SLD)$                  | 0.1513 ± 0.0021 | 0.1479                   |
| $\sin^2\theta^{\text{lept}}(Q_{\text{fb}})$ | 0.2324 ± 0.0012 | 0.2314                   |
| $m_W \, [\text{GeV}]$       | 80.392 ± 0.029 | 80.371                   |
| $\Gamma_W \, [\text{GeV}]$  | 2.147 ± 0.060 | 2.091                    |
| $m_t \, [\text{GeV}]$       | 171.4 ± 2.1 | 171.7                    |

**CDF:** 80.413/−0.048 GeV
Terra Incognita

- What is Dark Matter/ Dark Energy
- Why 3 families?
- Why 4 fundamental forces?
- Why are neutrinos so light?
What is the origin of mass?

Within SM, the Higgs field gives mass to particles.

- H not found yet
- But we have some idea on its whereabouts
Experimental constraints on Higgs

- Direct search at LEP
  - \( m_H > 114 \text{ GeV at 95\%CL} \)

- Indirect searches
  - Loop effects
  - \( m_t = 172.6 \pm 1.4 \text{ GeV} \)
  - \( m_W = 80.398 \pm 0.025 \text{ GeV} \)

\[
m_H = 87 \pm 36^{27} \text{ GeV}, \quad m_H < 160 \text{ GeV @ 95\% CL}
\]
What else we (think) know about it?

- Chaos, Solitons & Fractals Volume 30, Issue 2, October 2006 (E-infinity theory)
- Higgs mass is \(161.8033989\) GeV

Financial derivatives at ppx.popsci.com pricing the discovery of Higgs at Tevatron

T. Schucker compiled a list of Higgs predictions (58) at arXiv:0708:3344
Disclaimer

- We have not found the Higgs (yet)
  - If we did, you would have heard it already from blogs
- The road is more interesting than the destination
- There will be no limits in this talk
  - For an experimental physicist the data tells more stories than an abstract plot
  - Not to mention that I’d rather talk about the detector and the data than try to explain how arcane models were excluded or not
- I will concentrate on the SM Higgs
  - Most of the final states are similar
Tevatron at Fermilab

- Tevatron circulates protons (p’s) and anti-protons (pbar’s)
  - Not fundamental particles!
  - All the work is in making the pbar’s
- Particle beams collide at experiment sites (CDF, DØ)
  - Energy in C.O.M.: 2 TeV
- Tevatron is Energy Frontier right now
Record inst. Luminosity:
$3.15 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
Record weekly integrated luminosity:
$46.5 \text{ pb}^{-1}$
CDF detector

**General, multi-purpose detector**

- Focus on charged-particle tracking

**Features:**
- Silicon tracker
- Large radius tracking wire chamber (COT)
- Magnet (1.4T)
- Calorimeter
  - \(|\eta| < 3.6\)
- Muon chambers
  - \(|\eta| < 1\)

\[
\eta = -\ln(\tan \frac{\theta}{2})
\]
Triggering at hadron colliders

The physics cross sections span 12 orders of magnitude

<table>
<thead>
<tr>
<th>Process</th>
<th>At 100E30 every</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic ppbar</td>
<td>100ns</td>
</tr>
<tr>
<td>b and anti b quark</td>
<td>20µs</td>
</tr>
<tr>
<td>W</td>
<td>1 s</td>
</tr>
<tr>
<td>t and anti t quark</td>
<td>half hour</td>
</tr>
<tr>
<td>Higgs</td>
<td>~6 hours</td>
</tr>
</tbody>
</table>

Interesting events are rare

Keeping the rare events while rejecting the others is the job of the trigger
The CDF trigger system

- Hierarchical trigger system
  - 3 Levels of increasing sophistication in algorithms
  - Combination of custom build hardware and commodity PCs

- Premium on inclusive triggers
  - CDF can trigger on any event with a lepton (e or µ) above 20GeV
  - This allows broad open searches

- Hardware tracking for \( p_T \geq 1.5 \) GeV
  - Muon-track matching
  - Electron-track matching
  - Missing \( E_T \), sum-\( E_T \)
  - Silicon tracking
  - Jet finding
  - Refined electron/photon finding

- Full event reconstruction

CDF Detector

1.7 MHz crossing rate

L1 trigger

Dedicated hardware 42 \( L_1 \) buffers

30 kHz \( L_1 \) accept

Hardware + 4 \( L_2 \) buffers

L2 trigger

800 Hz \( L_2 \) accept

Linux farm (hundreds PCs)

L3 farm

100 Hz \( L_3 \) accept

disk/tape

A Higgs Story - Penn Seminar
Road to the Higgs

- \( gg \rightarrow H \)
  - \( H \rightarrow WW \) (high mass)
    - Easy signal
    - small(er) x section
  - \( H \rightarrow bb \) (low mass)
    - Tough signal
    - Larg(er) x-section
    - Associative prod

- \( W/ZH \)
  - striking signatures
  - low production
Higgs Story - Penn Seminar

H → WW

- **Basic Selection**
  - Two leptons
  - MET from ν
  - MET=missing $E_T$

- **Trigger:**
  - High $P_T$ leptons
  - MET

Angle between leptons provides good separation

**Backgrounds:**
- Drell-Yan
- WW

Stats is name of the game

Increase lepton acceptance
Identifying leptons

- Leptons at CDF
  - Electrons - EM deposition (plus track)
  - Muons - Tracks with associated hits in muon chambers (MIPs in calorimeter)

- The complication come from detector nonuniformity
  - Lots of subdetectors in fact

- Not all can be used in analysis (det. backg.)
- The trigger is not folded in

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
More leptons for H->WW

- Project the cylindrical detector geometry
  - Pseudorapidity ($\eta$) and azimuth ($\varphi$)
  - Different colors represent different muon candidates reconstructed in different muon chambers and/or different algo
\[ H \rightarrow b \bar{b} \]

- \[ \sigma_Z \cdot \text{BR}(Z \rightarrow b \bar{b}) = 1129 \pm 22 \text{ pb} \]
- The \( Z \rightarrow b \bar{b} \) process will set the scale of the problem

**Selection:**
- Two jets \( E_T > 22 \text{GeV} \)
- \( |\eta| < 1 \)
- Jets IDed as \( b \)

Background shape is determined from sidebands
Associated production

2 b jets + MET
Largest expected signal

2 leptons+2 b jets
Cleanest signal

Lepton+MET+2 b jets
Highest x-section
ZH → ννb̄b

Signal selection
- MET+2 jets (one identified as coming from b)

Trigger selection
- MET > 35 GeV
- 2 jets E_T > 15 GeV
- MET is difficult to trigger on
  - qq→qq dominant
  - E_q = E_{jet} + E_{mismeasured}
  - ∑ E_{mismeasured} = MET
  - MET(trigger) ≠ MET(offline)

Used in analysis

ZH MC

Passing trigger
Jet clustering in the trigger

- Jet clustering implemented in hardware using Run I algorithm
  - The calorimeter is viewed by the trigger on 24x24 $\eta-\phi$ map
  - The algorithm finds a seed (threshold 3GeV), then attaches any tower above the shoulder threshold (1 GeV) which touches any other tower in the cluster
- “Cone clustering” offline

“Pac-Man”

Trigger rate grows to untenable values at high instantaneous luminosity
New calorimeter trigger

- Take advantage of modern technologies to implement “cone clustering” in hardware
- In operation since last summer
ZH→llb → b

- Cleanest signature
  - 2 leptons from Z
  - 2 jets (IDed as b)
- Main background:
  - Z+jets

Use the well identified Z→ll as tag

NN selection using multiple variables
**ZZ as a road mark**

- Same signature ($llb \bar{b}$)
  - $\sigma_{ZZ} = 1.5\text{pb}$
  - B.R. $Z \to b \bar{b} = 20\%$
- Can we find this first?
- Pre-road mark
  - $ZZ \to 4$ leptons

\[
(p\ p \to ZZ) = 1.4 \pm 0.7 - 0.6 \text{ pb}
\]

Combined with the $ll\nu\nu$ channel

<table>
<thead>
<tr>
<th>Category</th>
<th>Candidates without a trackless electron</th>
<th>Candidates with a trackless electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ$</td>
<td>$1.990 \pm 0.013 \pm 0.210$</td>
<td>$0.278 \pm 0.005 \pm 0.029$</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$0.014^{+0.010}_{-0.007} \pm 0.003$</td>
<td>$0.082^{+0.089}_{-0.060} \pm 0.016$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.004^{+0.016}_{-0.015} \pm 0.210$</td>
<td>$0.360^{+0.089}_{-0.060} \pm 0.033$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observed</th>
<th>2</th>
</tr>
</thead>
</table>

A Higgs Story - Penn Seminar
WH → ℓνb b

- Basic selection:
  - High Pt lepton
  - 2 high Et jets (b ID)
  - Large MET

- Backgrounds difficult
  - W+HF

b tagging an important ingredient
How to find a b

- Are b’s different than other quarks?
  - Long lifetime $c\tau = 450 \, \mu m$
  - Displaced vertices
  - Large hadron mass - opening angle for decays
    - High impact parameter for tracks in b jets
    - 40-60 $\mu m$ resolution for SVX (30 $\mu m$ from beam width)
  - Semileptonic decays (high momentum lepton)

Fit displaced tracks and cut on $L_{xy}$ significance
Findings those b’s better

There is a wealth of information in b decays.

- Complex and complicated by detector effects
- Synthesizing all this information is the name of the game

Combine multiple variable in a neural network and set the NN cut to a comfortable S/B
H→ττ

- Tough by itself
  - BR down by x10
- Associative production?
  - Lower BR
  - Taus are better than b
    - We actually have a Z→ττ
  - Don’t have to rely so hard on W/ Z purity
    - (τ τ jet jet) final states

- Combination of one leptonic and one hadronic decaying tau
- Efficiency about the same as for b, but <0.5% fake rate
**ττ+2jets**

Consider all possible channels

- WH+ZH+VBF+ggH

Lots of kinematics to separate signal from background
A final combination

Though I have tried, I could not escape showing a limit plot.
Conclusions

- CDF is way on its way towards the Higgs
- Detector improvements and new analysis techniques are the lifeline of any experimental physics endeavor
- There are many interesting BSM searches which I have not had time to go into
- Right now, the Tevatron and CDF are the high energy frontier of the world
- It will be a challenge to get to the Higgs but where is the fun without the challenge?
- “I haven't a clue as to how my story will end. But that's all right. When you set out on a journey and night covers the road, you don't conclude that the road has vanished. And how else could we discover the stars?”
MSSM Higgs

- MSSM is a SUSY model with 2 Higgs doublets
- 5 Higgs bosons: h, H, A, H+, H-
- 2 parameters MA and tanβ describe the MSSM Higgs sector

Production cross section enhanced by ~tan2 with respect to SM Higgs
- Braching ratio neutral Higgs:
  - 8% tau pairs
  - 90% b pairs
**gg→H→bbb(b)**

- Use data to obtain normalizations and templates for different heavy flavor production backgrounds
- Use three b tagged jets
- Fit using several variables of interest

**Limit is model dependent**
gg/bb->H->tautau

- Selection:
  - 1 leptonic tau
  - 1 had tau
- QCD background form the data
- EWK from MC
- Background and signal templates fit to data
QCD flavor production mechanisms
Experimental constraints on Higgs

- Direct search at LEP
  - $m_H > 114$ GeV at 95% CL

- Indirect searches
  - $M_t = 170.9 \pm 1.8$ GeV
  - $m_W = 80.398 \pm 0.025$ GeV

$m_H = 76^{+33}_{-24}$ GeV, $m_H < 144$ GeV @ 95% CL