Towards an Understanding of Electroweak Symmetry Breaking

Florence Canelli  Fermilab

January 24, 2008
What we know

Six quarks, six leptons
- including 3 neutrinos with small or zero masses

The pattern of fermions replicate itself 3 times

Electromagnetic force: Photon
Weak force: W+, W-, Z
- Unify into one elegant theory: electroweak

Photon and gluon appear to be massless
W and Z bosons are quite heavy
- $M_W \sim 80$ GeV
- $M_Z \sim 90$ GeV

Fermions have a variety of different masses
What we know

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  including 3 neutrinos with small or zero masses

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  Unify into one elegant theory: electroweak

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  $M_Z \sim 90$ GeV
Fermions have a variety of different masses

Electroweak symmetry is broken
How do we incorporate masses into the standard model without breaking the theory?

Simplest mechanism:
- Create a field that spans over the whole universe
- $W$ and $Z$ bosons acquire masses through degrees of freedom of the field
- Fermions acquire masses interacting with the Higgs field

This mechanism requires a new particle: Higgs boson

Finding the Higgs boson would confirm our theory of mass
Top quark being so heavy is the only fermion with significant coupling to the Higgs boson.

$$L = -\frac{m_f}{v} \bar{f} f h = -\frac{m_f}{v} (\bar{f}_L f_R + \bar{f}_R f_L) h$$

\(v = 256 \text{ GeV}, \ m_t = 175 \text{ GeV}

Top-Higgs couplings plays a special role?
Is top special?

- Top is the only fundamental fermion with a mass at the electroweak scale
- New physics may be discovered either in its production or its decay
- Top quark mass plays a special role in the standard model and beyond entering in loop corrections to most observables
In this talk

- **Top quark mass**: Constraining the Higgs boson mass
- **Top couplings**: Is there something new at the electroweak scale?
- **Top electroweak production**: Towards finding the Higgs boson
- Challenges and experimental techniques in hadron colliders
Run II
Proton antiproton collider at $\sqrt{s} = 1.96$ TeV
Integrated luminosity delivered and on tape $> 2.8$ fb$^{-1}$
Analyses in this talk use 1–2 fb$^{-1}$
Currently analyzing 2–2.3 fb$^{-1}$
Mainly produced via strong interactions: \( tt\bar{t} \)

Process discovered in 1995

But also via electroweak: single top

Evidence of this process found in 2006

\[
\sigma_{tt} = 6.7 \text{ pb}
\]

\[\sigma_{s\text{-channel}} = 0.9 \text{ pb}\]

\[\sigma_{t\text{-channel}} = 2.0 \text{ pb}\]
Top decay

- Top decays via electroweak interactions

- Due to large mass $m_t > m_W + m_b$
  and assuming unitarity:
  $\text{BR}(t \rightarrow Wb) \sim 100\%$

- Top decays before hadronizing
  $\Gamma \sim 1.4 \text{ GeV} \gg \Lambda_{\text{QCD}}$

- Hadronic decay swamped by multijet (QCD) background

- Require an electron or muon in the event
Top in real life

similar for t-channel
Top data is triggered requiring a high $p_T$ lepton in the event (examples):

- Electron
  - track
  - match to energy cluster
- Muon
  - track
  - match to hit on a muon chamber
Require an electron or muon:
- $E_T > 20$ GeV
- $|\eta_{\text{electron}}| < 2.0$, $|\eta_{\muon}| < 1.0$

Missing transverse energy (MET)
- MET $> 25$ GeV

Jets
- **ttbar** 4 or more jets with $E_T > 20$ GeV, $|\eta| < 2.0$
- **single top** 2 jets with $E_T > 20$ GeV, $|\eta| < 2.8$

At least one **b-tagged** jet
b-tagging

- Identify b-jets by exploiting the long lifetime of B hadrons and the large track multiplicity of their decay.

- Reduces background contamination processes with no b-quark content.

- Charm tagging rate ~10%
- Mistag rate ~ 0.5%
After single top selection with one or more b-tagged jets

Used to calibrate backgrounds

Single-top (Higgs)

Top properties: mass, couplings
In general, measurements of top quark properties need to reconstruct top quark 4-vectors
- Neutrino escapes detection (in analysis technique)
- Different ways to assign jets to partons (jet permutations)

Background events degrade measurement resolution and/or hide signal (later in single top)

Monte carlo modeling limitations (systematic uncertainties)

Reconstructing quark energies from jet energies (jet energy scale)
Jet energy scale

- Determine the energy of the quarks

- Correct for effects such as hadronization, calorimeter non-linearity and non-compensation, multiple-interactions, underlying event, algorithm shortfalls, etc.

- **Correction**: derived from data and Monte Carlo events

- **Uncertainty**: differences between data and Monte Carlo jet energies
Jet energy scale

⚠️ Tune the simulation

Calorimeter response in simulation tuned to data using $E/p$ from data from single track trigger, test beam, etc.

Pythia and Herwig for hadronization model

Underlying event with Pythia Tune A, Jimmy for Herwig

Multiple interactions: Pythia or vertex reweighting
Jet energy scale

**Tune the simulation**

Calorimeter response in simulation tuned to data using E/p from data from single track trigger, test beam, etc.

![Diagram of jet energy scale and particle interactions](image)

- **HAD**
- **EM**
- **Calorimeter jet**
- **Particle jet**

**Multiple interactions**: Pythia or vertex reweighting

- Pythia and Herwig for hadronization model
- Underlying event with Pythia Tune A, Jimmy for Herwig
Jet energy scale

Evaluate uncertainties:
data – Monte Carlo

- Single track
- Minimum bias
- Test beam

Largest systematic in top mass measurements
Jet energy scale

Dijet events: use to correct for differences in the calorimeters and non-instrumented regions (method used in UA1)

Trigger jet selected in well measured region (central) and above trigger $E_T$ threshold

Study momentum balance with probe jet
Jet energy scale

- Photon+jets and Z+jets: used to evaluate differences between data and Monte Carlo (systematic uncertainties)
- EM calorimeter scale well known
- Events with back-to-back jet to Z/photon

Z+jets

Photon+jets

Data Mean: -0.306 ± 0.002
Pythia Mean: -0.296 ± 0.002
Herwig Mean: -0.326 ± 0.003
Data RMS: 0.179 ± 0.002
Pythia RMS: 0.160 ± 0.002
Herwig RMS: 0.175 ± 0.002
Precision measurement of the top quark mass

PhD students: Brian Mohr (UCLA, 2007), Adam Gibson (Berkeley, 2006)

+ PhD students: Daryl Hare (Rutgers, 2008), Jacob Linacre (Oxford, 2008)
+ Postdoc: Sasha Golossanov (Fermilab)
A precise top quark mass measurement allows for prediction of the mass of the Higgs boson.

Top quark mass and Higgs mass are related to standard model observables and parameters through loop diagrams.

\[ M_W^2(1 - \frac{M_W^2}{M_Z^2}) = \frac{A^2}{1 - \Delta r} \]

\[ A = 37.2802 \text{ GeV} \]

\[ \Delta r \approx a + bm_t^2 + cln\left(\frac{M_H^2}{M_W^2}\right) \]

Constraint on Higgs can point to physics beyond the standard model.

Calculate probability densities by convoluting the differential cross-sections with the experimental resolutions and parton distribution functions and by integrating over all the possible parton quantities \( y \) that lead to the observed quantities \( x \)

\[
\bar{P}(x) = \frac{1}{\sigma} \int d^n \sigma(y) dq_1 dq_2 f(q_1) f(q_2) W(x, y)
\]
Experimental resolutions are considered well measured (lepton energies, angles) or parametrized from the Monte Carlo (jet energies)

\[ W(x, y) = \delta^3(p^y_{\text{lepton}} - p^x_{\text{lepton}}) \prod_{j=1}^{4} W_{\text{jet}}(E_j^x, E_j^y) \prod_{i=1}^{4} \delta^2(\Omega_i^y - \Omega_i^x) \]

- \( W_{\text{jet}} \) models transition of parton to jet
- \( b \) and light jet flavor parameterizations
- uses two Gaussian functions, one to account for the peak and the other to fit the asymmetric tails
Top mass measurement

Constrain the invariant mass of the non-b-tagged jets to be $80.4 \text{ GeV}/c^2$ (W mass from LEP measurements known very precisely) to measure the jet energy scale in-situ

$$P_{t\bar{t}}(x; m_t, JES) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int d\rho dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{\text{perm,}\nu} |M_{t\bar{t}}(m_t)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 W_{\text{jet}}(JESx, y)$$

lepton and jets 4-\text{vectors}

5 integrals: choose $M_{\text{top}}$, $m_W$ and jet energy of one of the jets from the W, because $|M_{tt}|^2$ is almost negligible, except near the peaks of the four BW within $|M_{tt}|$

LO matrix element

Six-body phase space
Top mass measurement

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5 integrals: choose $M_{\text{top}}$, $m_W$ and jet energy of one of the jets from the W, because $|M_{t\bar{t}}|^2$ is almost negligible, except near the peaks of the four BW within $|M_{t\bar{t}}|$. 

- LO matrix element
- Six-body phase space
- Lepton and jets 4-vectors
Constrain the invariant mass of the non-b-tagged jets to be 80.4 GeV/c² (W mass from LEP measurements known very precisely) to measure the jet energy scale in-situ.

\[
P_{t\bar{t}}(x; m_t, JES) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int d\rho dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{\text{perm,} \nu} |M_{t\bar{t}}(m_t)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 W_{\text{jet}}(JESx, y)
\]
We optimize the use of statistics by using much of the individual kinematical information in the event:

- well measured events contribute more information than poorly measured events
- all neutrino $p_z$ allowed are included
- the right jet permutation is always considered (along with the others)
- background contamination is separated from signal

$$P_{tt}(x; m_t, JES) = \frac{1}{\sigma_{tt}(m_t)} \int d\rho dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{\text{perm},\nu} |M_{tt}(m_t)|^2 \frac{f(q_1)f(q_2)}{|q_1| |q_2|} \phi_6 W_{\text{jet}}(JESx, y)$$

5 integrals: choose $M_{\text{top}}$, $m_W$ and jet energy of one of the jets from the W, because $|M_{ttt}|^2$ is almost negligible, except near the peaks of the four BW within $|M_{ttt}|$
Measuring top mass

✧ Calculate a probability density for a background hypothesis using a matrix element from the VECBOS MC generator subroutine

✧ Likelihood used to simultaneously fit $m_t$, $JES$, and signal fraction, $C_s$

$$L(C_s, m_t, JES) \propto \prod_{i=1}^{N\text{events}} \left[ C_s P_{t\bar{t},i}(m_t, JES) + (1 - C_s) P_{W+jets,i}(JES) \right]$$

✧ Test method using Monte Carlo events

<table>
<thead>
<tr>
<th>Process</th>
<th>Events in 955 pb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ ($\sigma_{t\bar{t}}=8.0$pb)</td>
<td>$145.1 \pm 16.5$</td>
</tr>
<tr>
<td>$W+jets$</td>
<td>$14.5 \pm 5.1$</td>
</tr>
<tr>
<td>non-$W$</td>
<td>$5.2 \pm 2.6$</td>
</tr>
<tr>
<td>EWK</td>
<td>$2.2 \pm 0.5$</td>
</tr>
<tr>
<td>Data</td>
<td>$167$</td>
</tr>
</tbody>
</table>

\[ p_0 = 0.26 \pm 0.21 \]

\[ p_0 = 1.03 \pm 0.02 \]
With 955 pb$^{-1}$ we measure

$$m_t = 170.9 \pm 1.6\,(stat) \pm 1.4\,(JES) \pm 1.4\,(sys)\,GeV/c^2$$

and JES = 0.99 ± 0.02(stat)

PRL 99, 182002 (2007)
Some example plots using the most probable configuration.
Systematic uncertainties

- Measurements are now systematically limited
- Some of them are limited by the number of events in Monte Carlo samples
- The lack of experimental understanding of radiation and b-JES are the main uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainties (GeV/c²)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES residual</td>
<td>0.42</td>
</tr>
<tr>
<td>Initial state radiation</td>
<td>0.72</td>
</tr>
<tr>
<td>Final state radiation</td>
<td>0.76</td>
</tr>
<tr>
<td>Generator</td>
<td>0.19</td>
</tr>
<tr>
<td>Background</td>
<td>0.21</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.12</td>
</tr>
<tr>
<td>b-JES</td>
<td>0.60</td>
</tr>
<tr>
<td>b-tagging</td>
<td>0.31</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.04</td>
</tr>
<tr>
<td>Lepton p_T</td>
<td>0.22</td>
</tr>
<tr>
<td>Multiple interactions</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>1.36</td>
</tr>
</tbody>
</table>
The latest Tevatron combination includes this result (winter 2007)

\[ m_t = 170.9 \pm 1.8 \text{GeV/c}^2 \]
Top quark mass hints at a low Higgs mass

Final Run I, 2004

- LEP1, SLD Data
- LEP2, pp Data

68% CL

m_H [GeV] 114 300 1000 Preliminary

m_t [GeV] 130 150 170 190 210

m_W [GeV] 80.2 80.3 80.4 80.5 80.6

68% CL

m_H [GeV] 114 300 1000

m_t [GeV] 150 175 200
With 4 fb\(^{-1}\) the stat+JES lepton +jets uncertainty will be \(\sim\)1 GeV/c\(^2\)

The systematic uncertainty is harder to predict.

New improvements from other top reconstruction channels using in-situ JES technique.

Very possible that by the end of Run II we will have measurements in other channels approaching 1.5 GeV/c\(^2\) by D0 and CDF.

Tevatron-only top mass uncertainty most likely will reach 1 GeV/c\(^2\).

\[mt\] uncertainties in lepton+jets channel

CDF result with 1 fb\(^{-1}\)
CDF result with 1.7 fb\(^{-1}\)
**Top mass at the LHC**

**Top factory:**
- $\sigma_{\text{ttbar}}$ LHC $\sim 160 \sigma_{\text{ttbar}}$ Tevatron
- $\sigma_{\text{W+jets}}$ LHC $\sim 6 \sigma_{\text{W+jets}}$ Tevatron
- S/B $\sim 1$ at Tevatron $\Rightarrow$ S/B $\sim 20$ at LHC

**Expected number of events in l+jets channel:**
- $130/\text{fb}^{-1}$ (Tevatron) $\rightarrow 20,000/\text{fb}^{-1}$ at LHC

**More radiation and more pile up**

**Precision on $m_t$** is estimated to be 1 GeV/c$^2$

**But by using the huge statistics to measure the mass in many different regions it should be possible to gain control of the systematic uncertainties and reduce the uncertainty even further**
- jet angles, b-jets with soft muons tagged, different number of interactions

![Histogram of top mass distribution](image_url)
Tevatron uses W mass from LEP to reduce the uncertainties in $m_t$ and calibrate JES.

LHC can use the Tevatron precise measurement of $m_t$ (and LEP W mass) to calibrate JES.

- Can calibrate light JES and b-JES and b-tagging algorithms.
- Requires b-tagging?

![Graph showing jet energy scale error (%) as a function of $p_T$ (GeV/c) for $\gamma + \text{jet}$ and $Z + \text{jet}$ channels.]

- Startup (source calib. + test beam + MC)
- $W$ fit from $t\bar{t}$
- $50\%$ reduced b-tag
- Full b-tag
- $1-10 \text{ fb}^{-1}$
Measurement of the top couplings

Postdocs: Mousumi Datta, Ricardo Eusebi (Fermilab)
Are there new interactions at a higher energy scale?

Important to directly measure the top couplings

The V-A character of the decay determines the W boson helicity fractions:

\[ F_0 = 0.70, \quad F^- = 0.30, \quad F_+ = 0 \]
Same technique as top mass but parametrizing the matrix element as a function $f_0$ assuming $f_+ = 0$ and using $m_t = 175 \text{ GeV/c}^2$.

\[
\begin{align*}
\int d\rho dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{\text{perm,}\nu} |M_{tt}(f_0)|^2 \frac{f(q_1) f(q_2)}{|q_1||q_2|} \phi_6 W_{\text{jet}}(x, y)
\end{align*}
\]
Use simulation to understand biases and estimate the expected uncertainties.

Use 4 or more jets.

### Events in 1.9 fb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt ($\sigma_{tt}=8.2\text{pb}$)</td>
<td>$417.3 \pm 56.8$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$46.4 \pm 16.0$</td>
</tr>
<tr>
<td>non-W</td>
<td>$17.8 \pm 16.2$</td>
</tr>
<tr>
<td>EWK</td>
<td>$11.0 \pm 6.7$</td>
</tr>
<tr>
<td>Data</td>
<td>468</td>
</tr>
</tbody>
</table>
Measurement of $f_0$

- Using 1.9 fb$^{-1}$ and assuming $f_+=0$ for $m_t=175$ GeV/c$^2$ we measure

$$f_0 = 0.637 \pm 0.084\,(\text{stat}) \pm 0.069\,(\text{sys})$$

- Consistent with standard model expectations

Next: perform analysis in 2D $f_0$ and $f_+$ (model independent)

<table>
<thead>
<tr>
<th>Systematic uncertainties (GeV/c$^2$)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>0.019</td>
</tr>
<tr>
<td>Initial state radiation</td>
<td>0.026</td>
</tr>
<tr>
<td>Final state radiation</td>
<td>0.020</td>
</tr>
<tr>
<td>Generator</td>
<td>0.050</td>
</tr>
<tr>
<td>Background</td>
<td>0.009</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.023</td>
</tr>
<tr>
<td>b-tagging</td>
<td>0.002</td>
</tr>
<tr>
<td>Method</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.069</strong></td>
</tr>
</tbody>
</table>
Electroweak single top production

PhD students: Peter Dong (UCLA, 2008)
Postdoc: Bernd Stelzer (UCLA)
Single top

- Predicted by the standard model but only evidence by D0 in Dec. 2006

- Same signature than WH production:
  - Single top irreducible background
  - Testing ground for experimental techniques such as triggers, selection, multivariate analyses, b-tagging, jet resolution algorithms

\[ \sigma_{s\text{-channel}} \sim 0.9 \text{ pb} \]

\[ \sigma_{WH} (m_H=120 \text{ GeV}) \sim 0.1 \text{ pb} \]
Single top

- It allows for the only direct measurement of $|V_{tb}|$ without assuming 3 generations of CKM matrix unitarity

\[ \sigma_{\text{singletop}} \propto |V_{tb}|^2 \]

- Tests the V-A structure of EWK interaction. Production rate proportional to V-A coupling

\[ \frac{ig}{2\sqrt{2}} \bar{t}\gamma^\mu (1 - \gamma^5)V_{tb}bW_\mu \]

- New physics can be inferred by comparing different production modes
Backgrounds!

Reduce backgrounds: good b-tagging, multivariate techniques

<table>
<thead>
<tr>
<th>Number of Events / 1.51 fb⁻¹</th>
<th>Single Top</th>
<th>Background</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(\ell\nu) + 2 jets</td>
<td>136</td>
<td>28300</td>
<td>~1/210</td>
</tr>
<tr>
<td>W(\ell\nu) + 2 jets + b-tag</td>
<td>61</td>
<td>1042</td>
<td>~1/17</td>
</tr>
</tbody>
</table>

Model all backgrounds: validate data and Monte Carlo

Normalize backgrounds: estimate the amount of expected background in the sample
**Backgrounds**

- **W+HF jets (Wbb/Wcc/Wc) ~60%**
  - ALPGEN + PYTHIA
  - W+jets normalization from data and heavy flavor fractions from ALPGEN

- **Mistags (W+ light flavor jets) ~20%**
  - Falsely tagged light quark or gluons
  - ALPGEN + PYTHIA
  - Mistag probability parameterization obtained from inclusive jet data

- **Top/EWK (WW/WZ/Z,ttbar) ~15%**
  - PYTHIA
  - MC normalized to theoretical cross-section

- **Non-W (QCD) 5% (about the same size as the signal!!)**
  - Multijets events with semileptonic b-decays or mismeasured jets
  - Anti-electron data sample
  - Fit low MET data and extrapolate into signal region
The $W$+jets contribution is not known a priori, due to large corrections to the calculable cross section at high order.

HF fraction from ALPGEN+PYTHIA
b-tagging efficiency from data
Calibrate the HF fractions by comparing $W$+1 jet data with ALPGEN jet MC
Correct for non $W$+jets events

$$N_{W\bar{b}b}^{data} = \left( \frac{N_{W\bar{b}b}}{N_{W+jets}} \right)^{MC} \epsilon_{b-tag} K_{HF} N_{data}^{W+jets}$$

CDF Run II Preliminary, $L=1.51\text{fb}^{-1}$

Note: similar for $W$+charm background
Non-W background

- Need to model background with data
- Model with anti-electron sample where at least one of the ID electron selection fails
- Obtain normalization fitting the missing $E_T$ distribution

Before b-tagging:

After b-tagging:

![Graph showing signal region before and after b-tagging with 99.4% and 89.6% probability for $\chi^2$ and KS tests, respectively.](image)
Although we expect ~60 single top events, we expect ~1000 background events.

The uncertainty on the background is about 3 times the size of the single top and hidden behind background.

**CDF Run II Preliminary, L=1.51 fb^{-1}**

### Predicted Event Yield in W+2 jets

<table>
<thead>
<tr>
<th>Category</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td>23.9 ± 6.1</td>
</tr>
<tr>
<td>t-channel</td>
<td>37.0 ± 5.4</td>
</tr>
<tr>
<td>Single top</td>
<td>60.9 ± 11.5</td>
</tr>
<tr>
<td>tt</td>
<td>85.3 ± 17.8</td>
</tr>
<tr>
<td>Diboson</td>
<td>40.7 ± 4.0</td>
</tr>
<tr>
<td>Z + jets</td>
<td>13.8 ± 2.0</td>
</tr>
<tr>
<td>W + bottom</td>
<td>319.6 ± 112.3</td>
</tr>
<tr>
<td>W + charm</td>
<td>324.2 ± 115.8</td>
</tr>
<tr>
<td>W + light</td>
<td>214.6 ± 27.3</td>
</tr>
<tr>
<td>Non-W</td>
<td>44.5 ± 17.8</td>
</tr>
<tr>
<td>Total background</td>
<td>1042.8 ± 218.2</td>
</tr>
<tr>
<td>Total prediction</td>
<td>1103.7 ± 230.9</td>
</tr>
</tbody>
</table>

**Observed**

1078
Extracting single top

- Similar idea to tt analysis: only 4-body phase space
- Calculate many probability densities using matrix elements from the MADEVENT subroutines

\[ P(x) = \frac{1}{\sigma} \int d\rho_{j1} d\rho_{j2} dp_\nu \sum_{\text{perm}} |M|^2 \frac{f(q_1) f(q_2)}{|q_1||q_2|} \phi_4 W_{\text{jet}}(x, y) \]

3 integrals: we choose those quantities measured the least precisely

4-body phase space

Signal: s-channel t-channel
Backgrounds: Wbb Wcc Wcj
Define ratio of probability density hypotheses as event probability discriminant (EPD):

\[
EPD = \frac{b \cdot P_{\text{singletop}}}{b \cdot P_{\text{singletop}} + b \cdot P_{Wb\bar{b}} + (1 - b) \cdot P_{Wc\bar{c}} + (1 - b) \cdot P_{Wc\bar{c}}}
\]

\(b\) = Neural Network b-tagger output

Separate tagged b-jets from charm/light jets using a NN trained with tracking information.
Multivariate techniques require validating input and EPD templates in various data control samples:

- W+2 jets data (veto b-jets, selection orthogonal to the candidate sample)
- Similar kinematics, with very little contribution from top (<0.5%)
MC modeling checks

CDF Run II Preliminary, L=1.51 fb⁻¹

Candidate Events vs. Lepton p_T [GeV/c]

Candidate Events vs. Leading Jet E_T [GeV]

Candidate Events vs. Second Jet E_T [GeV]

Candidate Events vs. Lepton Eta

Candidate Events vs. Leading Jet Eta

Candidate Events vs. Second Jet Eta

Candidate Events vs. dPhi(MET, Jet1)

Candidate Events vs. dR(Jet1, Jet2)

Candidate Events vs. W Transverse Mass [GeV]

KS: 50.1%
On/Off: 14.2/24: 92.6%

KS: 0.4%
On/Off: 35.0/28: 13.2%
Using 1.5 fb\(^{-1}\) we measure

\[ \sigma_{\text{singletop}} = 3.0^{+1.2}_{-1.1}\,\text{pb} \]

Median p-value = 0.13% (3.0\(\sigma\))

Observed p-value = 0.09% (3.1\(\sigma\))
(new) Single top & Higgs

PhD students: Peter Dong (UCLA), Barbara Alvarez, Bruno Casal (Cantabria)
Postdocs: Bernd Stelzer (UCLA), Craig Group, Enrique Palencia (Fermilab)
Technique and improvements in single top are now implemented in Higgs searches

$$EPD = \frac{b \cdot P_{WH}}{b \cdot P_{WH} + b \cdot P_{st} + b \cdot P_{Wbb} + b \cdot P_{tt} + (1-b) \cdot P_{Wcc} + (1-b) \cdot P_{Wcj}}$$
Maximizing sensitivity

- Added the 3-jet bin: greater ttbar contamination
- Increased acceptance by 35% including a non-lepton trigger (MET + jets) All new muons but CMPU, CMX

New EPD with more probability densities in the 2 and 3 jets bins: ttbar and W+light
More information in jet transfer functions (larger cone size, \( \eta \)) and added gluon jets
4 improvements

✦ Using the single top analysis as a benchmark:

✦ + matrix element improvements: 9.2% gain, mostly ttbar matrix element and new transfer functions

✦ + new muons from MET+jets trigger: 8% gain

✦ + two- and three-jet bin combined: 3.5% gain
**2004:** Simple analysis while refining Monte Carlo samples and analysis tools

First Tevatron Run II result using 162 pb\(^{-1}\)

\[ \sigma_{\text{single top}} < 17.5 \text{ pb at 95\% C.L.} \]

- Development of powerful analysis techniques (Matrix Element, NN, Likelihood Discriminant)
- NN Jet-Flavor Separator to purify sample
- Refined background estimates and modeling
- Increase acceptance (forward electrons)
- 10x more data

**2006:** Established sophisticated analyses Check robustness in data control samples

- Refined background estimates and modeling
- Increase acceptance (forward electrons)

**2007:** Evidence for single top quark production using 1.5 fb\(^{-1}\) (expected and observed!)
Higgs at the LHC

- For a Higgs mass < 135 GeV
  - Tevatron may find $H \rightarrow bb$
  - LHC should discover $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$
  - Complementary results would help to confirm if it is the Higgs boson

- LHC will also have access to $t\bar{t}H$ with $H \rightarrow bb$
  - Important to measure Yukawa coupling
  - Enhanced in MSSM by 10–20% compared to standard model
  - Very challenging channel!
  - One lepton: tracking, alignment, trigger
  - Many jets: calorimeter EM and HAD calibration, JES
  - Missing transverse energy
  - $b$-jets: good (very good) $b$-tagging
    - $t\bar{t}$bar events will enable understanding of these tools, eg. $R = BR(t \rightarrow Wb) / BR(t \rightarrow Wq)$
  - Multivariate techniques to separate signal and background

Multivariate techniques to separate signal and background

Complementary results would help to confirm if it is the Higgs boson
Summary

- Top quarks offer a way to learn about the Higgs boson and explore the electroweak scale
  - Precise measurements of $m_t$ at the Tevatron will reach 1 GeV/$c^2$
  - Couplings begin to be systematically limited
  - Single top in the horizon
  - Searches for Higgs boson at the Tevatron are rapidly improving

- Top quark physics is experimentally challenging and rich
  - It is at the core of hadron collider physics
  - Produced many experimental techniques for high $p_T$ physics
    - Triggers, jet energy scale, b-tagging, etc.
    - Multivariate techniques
    - Shape and rate of backgrounds
  - It will play a main role in calibrating and understanding the LHC experiments

- These are the most exciting years!
Systematic uncertainties can affect rate and template shapes

- Rate systematics give fit templates freedom to move vertically only
- Shape systematics allow events to ‘slide horizontally’ (from bin to bin)