Recent Top/EW Results from CDF

Thomas Wright
University of Michigan

For the CDF Collaboration
Introduction

• The nature of electroweak symmetry breaking is one of the top unsolved problems in particle physics

• Whatever the mechanism, high mass objects are the right laboratory to study it
  – Gauge bosons and top quarks

• CDF is performing a wide variety of measurements within the top/EW arena

• Results shown today are just a sample of the work going on

• Electroweak results
  – WW/WZ → lv + 2 jets
  – W charge asymmetry

• Top results
  – Top production cross section
    • B-Tagging
    • Kinematic fitting
  – Anomalous semileptonic decays
  – Top mass measurements
    • Template fitting
    • Matrix element methods
Diboson Production

- CDF has two RunII (200 pb\(^{-1}\)) measurements of \(\sigma_{WW}\)
  - Cross sections consistent with the expected value of \(\sim 13\) pb
- Still no observation of WZ/ZZ
  - \(\sigma \leq 15.2\) pb\(^{-1}\)
- CDF has recently performed a search for WW/WZ production, where \(W \rightarrow l\nu\) (l=e,\(\mu\)) and W/Z decays hadronically into two jets
  - Higher branching ratio but also much higher backgrounds
  - Dominant background is \(W+2p\) production, which is constrained by fitting to dijet mass sidebands
- Fitting signal+background to signal region returns

\[
N_{\text{sig}} = 66\pm78\pm34 \quad (N_{\text{SM}} = 91)
\]

\[
N_{\text{sig}} < 40\text{ pb} \quad (95\% \text{ CL})
\]
Anomalous Couplings

- There are other things you can do with a WW sample besides measure a cross section
  - Test for anomalous triple-gauge-boson couplings
- In one “standard” SM extension, anomalous interaction terms are parametrized by $\Delta \kappa$ and $\lambda$
- The $P_T$ of the $W$ formed from the lepton and the missing $E_T$ ($v$) is found to be the most sensitive probe – anomalous VV pairs are produced with high $P_T$
- 95% CL limits obtained are:
  - $-0.42 < \Delta \kappa < 0.58$
  - $-0.32 < \lambda < 0.35$
W Charge Asymmetry

- The asymmetry in $x$ between up and down quarks in the proton results in a charge asymmetry in $W$ rapidity

$$A(y_W) = \frac{d\sigma_+ / dy_W - d\sigma_- / dy_W}{d\sigma_+ / dy_W + d\sigma_- / dy_W}$$

  - Sensitive to PDFs

- Have previously measured lepton rapidity asymmetry rather than $A_W$ (CDF RunII results already published in PRD)

  - However, the underlying $W$ asymmetry is distorted by the angular structure of $W$ decays (charged lepton comes out opposite to $W$ direction)

- Because the true $W$ asymmetry tends to be larger, it is a more statistically powerful probe
Using the W mass one can solve for the neutrino $P_z$ up to a twofold ambiguity.

Weight the two solutions according to their likelihood, based on the decay angle $\cos\theta^*$ and cross section $\sigma(y_W)$.

One complication is that $\sigma(y_W)$ depends on the asymmetry that’s being measured!
  
  Iterate until the best description of the data is obtained.

A Monte Carlo sensitivity study shows that the resulting W asymmetry is much more powerful at discriminating between various PDF sets than the lepton rapidity asymmetry.

Preliminary evaluations of systematic errors indicate that they should be small compared to statistics.

Still a little work to do on backgrounds and lepton charge misidentification.
Top Event Selection

- Top quarks are (usually) pair-produced at the Tevatron and decay $t \rightarrow Wb$ ~100% of the time in the SM
- Top event selection is based on the decays of the $W$’s
  - Dilepton: require two high-$p_T$ leptons, large missing $E_T$ from the neutrinos, and at least two jets
  - Lepton+jets: require one high-$p_T$ lepton, large missing $E_T$, and at least three jets
- The signal/background can be enhanced by tagging one or more of the jets as a b-jet, using displaced tracks, reconstructed vertices, or lepton tags
  - Improved forward tracking has extended our displaced-vertex tagging coverage vs jet pseudorapidity
  - Event tagging efficiency for $t$-tbar is ~60%, with ~0.5% per-jet mistag rate for the vertex tagger
Top Cross Section with B-Tagging

- This result uses the lepton+jets selection, and requires either:
  - $\geq 1$ b-tagged jets
    - $S/B = 102/36$
  - $\geq 2$ b-tagged jets
    - $S/B = 29.7/3.3$
- Signal region is $\geq 3$ jets, lower multiplicity bins are control regions to test background estimation
- Dominant background comes from $W+$jets, where the jets are true tagged heavy flavor or mistagged light flavor
- Cross sections for 318 pb$^{-1}$ are:
  $$\sigma_{tt} = 7.9 \pm 0.9 \pm 0.9 \text{ pb (}\geq 1 \text{ tag)}$$
  $$\sigma_{tt} = 8.7 \pm 1.7 \pm 1.5 \text{ pb (}\geq 2 \text{ tag)}$$
Top Cross Section with Kinematics

- We also measure a top cross section using the inclusive lepton+jets selection without requiring any b-tagging.
- Signal/background is lower, have to separate using a fit rather than just counting.
- A neural network trained to separate top from W+jets events is used.
- An “EW background” template is formed by passing W+3p, Wbb+1p, WW+1p, etc, MC events through the network, and weighting by their SM cross sections.
- The QCD template is derived from events in the data where the lepton is not isolated, and fixed in the fit at the measured level of 4.6%.

**CDF Preliminary (347 pb⁻¹)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Events</th>
<th>Fitted $t\bar{t}$</th>
<th>$\sigma(t\bar{t})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \geq 3$ jets</td>
<td>936</td>
<td>$148.2 \pm 20.6$</td>
<td>$6.0 \pm 0.8 \pm 1.0$ pb</td>
</tr>
<tr>
<td>$W^+ \geq 4$-Jet</td>
<td>210</td>
<td>$80.9 \pm 15.0$</td>
<td>$6.1 \pm 1.1 \pm 1.4$ pb</td>
</tr>
</tbody>
</table>
Top Cross Section Summary

- For comparison purposes we evolve all cross sections to $m_t = 175$ GeV/c$^2$
  - Increases values by $\sim 0.2$ pb compared to $m_t = 178$ GeV/c$^2$
- Updated results in the dilepton and all-hadronic decay channels and using the jet probability tagger soon
- Working on a combination of the results
Anomalous Semileptonic Decays

- In Run I, CDF observed an excess of events in $W$+jets where a jet was tagged with both the displaced-vertex and “soft lepton” taggers (Phys. Rev. D69, 072004)
- An example scenario that could produce such an effect is light sbottom production
- Take a look in the Run II sample using the displaced-vertex and soft muon taggers
- Analysis is very similar to the b-tagged top cross section measurements, just have to work out the efficiency and mistag correlations between the two taggers
- In 162 pb$^{-1}$ we see no evidence for anomalous production so far
- Work is progressing to turn this into cross section X BR limits
Top Mass Measurements

- The mass of the top quark is a most interesting SM parameter
  - Can be predicted from a fit to the LEP/SLD Z-pole measurements
  - Along with $M_W$, constrains the SM Higgs mass
- Measurements can be roughly divided into two categories
  - Template methods: Reconstruct a top mass for each event in the sample, then compare to MC templates constructed with different top masses and interpolate to the best match
  - Matrix element methods: Using differential cross sections, calculate a probability for each event as a function of $m_t$, choose the mass that maximizes the likelihood of the entire sample
- No matter how you do it, limiting systematic uncertainty is the energy scale of jets in the calorimeter
Lepton+Jets Template Method

- Lepton+jets selection with ≥4 jets
- Determine the jet assignments using a $\chi^2$ function, imposing W mass constraints and requiring the two top masses to be equal
- B-tagging reduces permutations
- Jet energies are allowed to float within their resolutions
- Can optionally float the overall jet energy scale (with a constraint) – use the W mass to improve the precision
- Configuration with the lowest $\chi^2$ used to compute the top mass for each event
- Build templates for various top masses and also for the background, and find the best fit

$$m_t = 173.5^{+2.7}_{-2.6} \pm 2.5 \pm 1.7 \text{ GeV}/c^2$$

$$m_t = 173.5^{+4.1}_{-4.0} \text{ GeV}/c^2$$
Dilepton Template Method

- Template-based methods can also be used in the dilepton decay channel
  - With two neutrinos, it’s not possible to reconstruct the t-tbar system – have to make an assumption ($\eta(v), \phi(v), P_z(tt)$)
  - Samples are smaller than in lepton+jets (S/B = 33/13)
- Scan over possible pseudorapidity values for each of the two neutrinos
- For each pair of neutrino $\eta$, compute the likelihood to get the observed missing-$E_T$ as a function of $m_t$
- Integrate over neutrino $\eta$‘s to get a likelihood curve for each event vs $m_t$
  - Choose the most probable $m_t$ for each event
- Rest of the analysis proceeds exactly as for the lepton+jets template result

$m_t = 170.6^{+7.1}_{-6.6} \text{(stat)} \pm 4.4 \text{(syst)} \text{ GeV/c}^2$
Dynamical Likelihood Method

- Template methods give you one top mass value per event, but don’t make use of how “top-like” the events are.
- Matrix element methods incorporate more information by using a differential cross section to characterize the likelihood of each event given a value of $m_t$.
- Multiply all resulting event probabilities to get a sample likelihood and maximize vs $m_t$.
- A leading-order matrix element doesn’t exactly describe top events.
  - Make a $\sim 2$ GeV/c$^2$ correction to the fitted $m_t$.
- Only b-tagged lepton+jets events with exactly four jets (63 vs 138).

$$m_t = 173.8^{+2.7}_{-2.5} \text{(stat)} \pm 3.3 \text{(syst)} \text{ GeV/c}^2$$

$$m_t = 173.8^{+4.3}_{-4.1} \text{ GeV/c}^2$$

$$L^i(M_{top}) = \sum_{l_t} \sum_{l_z} \frac{2\pi^4}{\text{Flux}} F(z_a, z_b, p_T) \left| M \right|^2 w(x, y) dx$$

$L^i =$ likelihood for event $i$

$F =$ parton dist. function for $tt$ system $p_T$

$M =$ production+decay matrix element

$w =$ partons $x \leftrightarrow$ observables $y$

Sums are over jet/parton assignments and the two neutrino $P_z$ solutions.

CDF Run II Preliminary (318 pb$^{-1}$)
**Dilepton Matrix Element**

- Matrix element method applied for the first time to dilepton events
  - Same problem of two neutrinos
  - Solution is to integrate over their momenta → vector of observables $y$ will be smaller than parton vector $x$ in this case
- In addition to signal, these results also use differential cross sections for the background processes WW, Drell-Yan, and W+jets (fake lepton)
- Calculate probabilities for each event to be any of the signal or background types
- Combined likelihood is a sum of signal and background probabilities, weighted by the expected number of each type
- Make a ~1 GeV/c$^2$ correction for non-LO-ness of real top events

$$m_t = 165.3 \pm 6.3\,(stat) \pm 3.6\,(syst) \text{ GeV/c}^2$$
Top Mass Summary

- TevEWWG has produced a new average
  - $\delta m_t = 3.4 \text{ GeV/c}^2$ (was 4.3 in RunI)
  - Currently using most precise single measurement per decay channel from each experiment
  - Work ongoing to combine results within each channel (including CDF results from RunI)
- Floating JES is limited by statistics – can reach our RunII goal of $\delta m_t = 2-3 \text{ GeV/c}^2$

Jet Energy Scale from $W\rightarrow jj$

Preliminary Tevatron Average (pending final CDF/D0 review)

- World Average (CDF+D0) ($L = 358 \text{ pb}^{-1}$)
  - $174.3 \pm 2.0 \pm 2.8$
- Run 1 D0 Lepton+Jets ($L = 100 \text{ pb}^{-1}$)
  - $180.1 \pm 3.6 \pm 3.9$
- Run 1 D0 Lepton+Jets ($L = 318 \text{ pb}^{-1}$)
  - $168.4 \pm 12.3 \pm 3.6$
- Lepton+Jets: $M_{\text{top}}^{\text{reco}} + W \rightarrow jj$ ($L = 318 \text{ pb}^{-1}$)
  - $173.5 \pm 2.7 \pm 3.0$
- Dilepton: Matrix Element ($L = 339 \text{ pb}^{-1}$)
  - $165.3 \pm 6.3 \pm 3.6$
- Lepton+Jets: DLM ($L = 318 \text{ pb}^{-1}$)
  - $173.8 \pm 2.7 \pm 3.3$
- Dilepton: $v$ weighting ($L = 358 \text{ pb}^{-1}$)
  - $170.6 \pm 7.1 \pm 4.4$
Top Mass Interpretation

- Martin Grunewald was kind enough to prepare a blueband plot using the new CDF \( m_t \) result (lepton+jets only)
  - \( m_H = 94 + 54 - 35 \) GeV/c\(^2\)
  - \( m_H < 208 \) GeV/c\(^2\) @ 95% CL

- The fit is moving further into the LEP-II excluded region but of course there is still plenty of probability outside of it

- Similar fits can be done in the context of the MSSM (thanks to Sven Heinemeyer and Georg Weiglein)

- The new \( m_t \) prefers a lower mass scale for SUSY particles, which could be good news for Tevatron discovery prospects (or bad news for the MSSM)
Summary

- CDF has a wide array of RunII top/EW analyses using 200-300 pb\(^{-1}\) either published or in progress
  - EW: 5 published, 1 submitted, 2 in preparation
  - Top: 5 published, 3 submitted, 9 in preparation
- As sample sizes increase to the multi-fb\(^{-1}\) range, can perform more intensive studies of the particle and event properties
  - W mass, W width (from R), gauge boson couplings
  - Top mass, charge, spin, branching ratios
  - Single-top production
  - Search for WW and tt resonances
- Analysis strategies will evolve to lessen/avoid the current limiting systematic errors
- We have come a long way but it’s just the beginning