Top Studies at CDF

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Tevatron, top and CDF >20 years

1985-2011

1.96 TeV

Top Discovery
1994-1995

12 fb\(^{-1}\) delivered
10 fb\(^{-1}\) on tape
Why top is so interesting?

Heaviest quark known (∼172.5 GeV/c²)
  ➢ Due to its mass decays before hadronization
  ➢ No bound states («top mesons», «Upsilon-like»)
  ➢ «direct» access to production and decay vertex
    ➢ Couplings, CKM elements..
  ➢ Related to Higgs mass through loops
    ➢ Precision measurement of $M_W$, $M_{top}$
    ➢ Stability of our Universe...
  ➢ Yukawa coupling ∼1
    ➢ Anything special about top and its relation to EWSB?
      ➢ Window to new physics?

Two different production mechanisms
  ➢ Ewk processes
  ➢ Strong interactions
What can we study?

Production cross section
Asymmetry
Resonances
EWK single top, $V_{tb}$

Mass
Lifetime/Width
charge
Helicity
Spin
charge
correlation
Branching Fractions
FCNC decays

Will concentrate on newest CDF results

See Yvonne Peters’ talk for Top Mass..
Tools: physics objects

- High Pt lepton (e or mu)
  - Isolated as coming from W

- 2 or 3 Jet with large $E_T$
  - 20 GeV at CDF
  - $|\eta|<2.8$ Tevatron

- Missing $E_T$ (MET)
  - 25 GeV (CDF), 20/25 (D0)

- b-tagging of secondary vertices
  - With a variety of tools (from tracks displaced from the primary to NN algorithms)
Production vertex

Top Pair production

- ~85 % through qqbar annihilation
- Calculated assuming BF (t\@\rightarrow Wb)\sim 100%
- Classified through W decay path
  - Dilepton (both Ws decay leptonically)
  - l+jets (in W decays into quarks)
  - All-hadronic (both Ws decay into quarks)
- CDF does not exploit W\@\rightarrow \tau \nu decays
  - Dilepton (e,\mu) \sim 5\%: llvvbb
  - l+jets (~30\%): lv qqbb
  - All-hadronic (~45\%):qqqqbb
Inclusive cross section

CDF results contribute to TeV combination by 60%

Only dilepton analysis uses the whole dataset

Theoretical prediction accuracy: 4.4%

\[ \sigma = 7.35^{+0.11}_{-0.21} \text{ (scale)}^{+0.17}_{-0.12} \text{ (PDF)} \]

CDF: 7.63 ± 0.5 pb (6.5%)
CDF studied $\theta_t$ angle between proton and top quark direction in ttbar ref frame

~Agreement with SM

Characterize using Legendre polynomials

First moment shows tension with prediction

PRL 111, 182002 (2013)
$A_{FB}$ in $tt\bar{t}$ events

$A_{FB}$ is defined as $A_{FB} = \frac{N_{\Delta Y>0} - N_{\Delta Y<0}}{N_{\Delta Y>0} + N_{\Delta Y<0}}$

$\Delta y = y_t - y_{t\bar{t}}$

- Inclusive $A_{FB} = 8.8 \pm 6.6 \%$

- Deviation from SM generated by
  - Axial Vector, $Z'$ exchange, $W'$ interaction
  - BSM scenarios should however be consistent with measured
    - $\sigma_{tt}$, $d\sigma/dM_{tt}$, LHC results
Old and new results

$A_{FB}$ in $l$+jets: observed $6.6 \pm 2\%$, at parton level $16.4 \pm 4.7 \%$

- Mass and rapidity dependence

New results: leptonic asymmetry in dilepton channel
- Combination of $t\bar{t}$bar leptonic $A_{FB}$
- $A_{FB}$ in $b\bar{b}$ pairs (not covered here)

PRD 87,892002(2012)
We can study the leptonic observable:

\[ A_{FB}^{l} = \frac{N(q_{l}\eta_{l} > 0) - N(q_{l}\eta_{l} < 0)}{N(q_{l}\eta_{l} > 0) + N(q_{l}\eta_{l} < 0)} \]

- \( A_{FB}^{l} \) correlated to top \( A_{FB} \)
- \( l+jets : 9.32^{+3.2}_{-2.9}\% \) (SM: 3.8±0.3%)

Best fit curves shown for NLO prediction (green) and measured (black).

PRD 88,072003(2013)
Leptonic asymmetry in dilepton channel

- Comparison of the number of leptons as a function of $q_\eta$, wrt SM (POWHEG) prediction

Asymmetric part of the distribution, with best fit and expectations

Result:

$$A_{FB}^l = (7.2 \pm 5.2\,\text{(stat)} \pm 3\,\text{(syst)})\% = (7.2 \pm 6.0)\%$$

SM Exp: (3.8\pm 3)\%
Combination of leptonic asymmetries

- Two measurements are combined using BLUE
  - $l+$jets uses 3864 events, 72.8% purity:
    - $A_{FB}=9.4^{+3.2}_{-2.9}\%$
  - Dilepton channel uses 569 events, 71.8% purity
    - $A_{FB}=7.2\pm6\%$
- Combined result
  - $A_{FB}=9.0^{+2.8}_{-2.6}\%$
  - (80%$l+$jets, 2.6% correlation)
- Combined result is $\sim1.8\sigma$ from SM

Submitted to PRL
arXiv.1404.3698v1
$|V_{tb}|$ and BF

Decay vertex is related to CKM element $|V_{tb}|$

- Direct studies of the decay vertex
- Measurement of branching fractions
- Direct measurement of $|V_{tb}|$
- Detection of single top events, measurement of cross section
Ratio BF(\(t \rightarrow W_b\))/BF(\(t \rightarrow W_q\)) in \(t\bar{t}\)bar dilepton sample

- In the SM:
  \[ \sum |V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1 \]

- Comparison between observed data and expectations in samples (ee, \(e\mu\), \(\mu\mu\)) \(x(0,1,2)\) (leptons)(b-tags)

- Check: x-section:
  \[ \sigma = 7.64 \pm 0.55\text{(stat)} \pm 0.46\text{(lum)} \text{ pb} \]

- BR is measured fitting a ML

\[ R = \frac{\mathcal{B}(t \rightarrow W_b)}{\mathcal{B}(t \rightarrow W_q)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} \]

\begin{tabular}{|c|c|}
\hline
Parameter & Result \\
\hline
\(R\) & 0.87 \pm 0.07 \\
\(|V_{tb}|\) & 0.93 \pm 0.04 \\
\hline
\end{tabular}

\( V_{tb} > 0.85 \) @95% CL
R in l+jets

CDF measured R in the l+jets channel

- Study the number of b-tagged jets in ttbar-enriched sample:
- Simultaneous fit to cross section and R:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>$0.94 \pm 0.09$ (stat+syst)</td>
</tr>
<tr>
<td>$\sigma_{pp\to tt}$</td>
<td>$7.5 \pm 1.0$ (stat+syst) pb</td>
</tr>
<tr>
<td>$\rho R\sigma_{pp\to tt}$</td>
<td>$-0.434$</td>
</tr>
</tbody>
</table>

$|V_{tb}| > 0.89$ @95 %CL

PRD 87,11 111101(2013)

Work in progress on combination
What is single top?

Electroweak production of top quark

➢ All Feynman diagrams below have a Wtb vertex

<table>
<thead>
<tr>
<th></th>
<th>t</th>
<th>s</th>
<th>Wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>$2.26\pm0.2$</td>
<td>$1.04\pm0.1$</td>
<td>$0.3\pm0.06$</td>
</tr>
<tr>
<td>LHC (7 TeV)</td>
<td>$64.2\pm2.4$</td>
<td>$4.6\pm0.2$</td>
<td>$15.7\pm1.1$</td>
</tr>
<tr>
<td>LHC (8 TeV)</td>
<td>$87.8\pm3.4$</td>
<td>$5.6\pm0.3$</td>
<td>$22.4\pm1.5$</td>
</tr>
</tbody>
</table>

s-channel difficult at the LHC
Access to the $W$-$t$-$b$ vertex

- probe V-A structure
- access to top quark spin

Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:

- Is this Matrix 3x3?
- Is there a 4th generation?
- Does unitarity hold?

$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 \overset{?}{=} 1$

Precision electroweak measurements rule out "simple" fourth generation extensions, but see for example:

Sensitivity to New Physics

- New physics may affect the rate of t and s channel differently

- Flavor changing neutral currents (t-Z-c, t-γ-c, t-g-c)

  - heavy W’ boson
  - charged Higgs H^+
  - Kaluza Klein excited W^{kk}

T. Tait, CP Yuan PRD63, 014018 (2001)
The challenge is

- To measure a process with yield smaller than background fluctuations
- Separate the different (s,t) components

Strategy

- Combine several channels
- ANN to identify the signal
- Extract CKM element:

\[ |V_{tb}|^2 = |V_{tb}^{SM}|^2 \times \frac{\sigma^{obs}}{\sigma^{SM}} \]

s+t:

- l+jets analysis (lnbb)
  - s+t and s vs t
- Met-bb (forget l)
  - s+t and s vs t

s-optimized analysis

- Evidence for single top in s-channel
  - Eventually combined with D0
- s-channel observation
  - 6.3 \( \sigma \) (Tev combination)
  - see Yvonne Peters's talk
Results (s+t channel)

- Extract separate s and t channel x-sections (ratio fixed to SM value)
- Obtain $|V_{tb}|$ by integrating the ML and assuming a flat prior $0 < |V_{tb}| < 1$

l+jets, 7.5 fb$^{-1}$:

$|V_{tb}| = 0.95 \pm 0.09$ (stat+syst) $\pm 0.05$ (theo)

$|V_{tb}| > 0.78$ (95% C.L.)

Combining with the MET bb analysis: $|V_{tb}| > 0.84$ (95% C.L.)

New
CDF optimized its analyses to observe single top production in the s-channel

- New l+jets and MET+jets optimized analyses
- Innovative multivariate tagger (used in VH evidence)
- NN s-optimized

\[ \sigma_s = 1.41^{+0.44}_{-0.42} \text{ (stat+syst) pb} \]

\[ \sigma_s = 1.12^{+0.61}_{-0.57} \text{ (stat+syst) pb} \]

PRL 112, 221801 (2014)

PRL 112, 231804 (2014)
Conclusions

Top studies are still ongoing

- Some channels are unique to the Tevatron
  - At least «challenging» at the LHC
- $A_{FB}$ still an open question
  - Will it be solved?
- Some measurements are real legacies
  - Both in terms of results and of technical developments
  - CKM element $V_{tb}$ deserves a closer look
- Is the third generation the path to new physics?