Top quark pair production and top quark properties at CDF

Chang-Seong Moon*

on behalf of CDF collaboration

Université Paris Diderot/CNRS & INFN-Sezione di Pisa

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CDF Experiment and Dataset

- 1 km Radius Ring
- 2 million proton-antiproton collisions per second
- Run I (1992~1996): ~110 pb\(^{-1}\), 1.8 TeV
- Run II (2001~2011): ~10 fb\(^{-1}\), 1.96 TeV
Any deviation from SM could indicate **New Physics** signal indirectly.
Top Pair Production and decay

Most top pair production by Strong interaction at the Tevatron

One top pair each $10^{10}$ inelastic collisions at $\sqrt{s} = 1.96$ TeV
- Observed thousands of events in Run II

Decay channels classified by W decays

Top pair decay channels ($l=e,\mu$)
- Dilepton: $l\nu l\nu bb$ (5%)
- Lepton+jets: $l\nu qqbb$ (30%)
- All-hadronic: $qqqqbb$ (45%)

### Top Pair Decay Channels

<table>
<thead>
<tr>
<th>Decay</th>
<th>electron+jets</th>
<th>muon+jets</th>
<th>tau+jets</th>
<th>all-hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$e^-\mu^-$</td>
<td>$\mu^-\tau^-$</td>
<td>$\tau^+\bar{\tau}$</td>
<td>tau+jets</td>
</tr>
<tr>
<td>$e^-\mu^-$</td>
<td>$e^-\mu^-$</td>
<td>$e^-\mu^-$</td>
<td>electron+jets</td>
<td></td>
</tr>
<tr>
<td>$W$ decay</td>
<td>$e^+$</td>
<td>$\mu^+$</td>
<td>$\tau^+$</td>
<td>$u\bar{d}$</td>
</tr>
</tbody>
</table>
Top quark width

- Top quark has the largest decay width of the known fermions in the SM prediction. ($\Gamma_{\text{top}} \sim 1.3$ GeV at $M_{\text{top}} = 172.5$ GeV/$c^2$)
- Direct measurement of the top-quark width is performed in fully reconstructed lepton + jets events by using the full CDF Run II data set

Results are consistent with SM prediction. No evidence of non-SM physics in the top-quark decay.
- $1.10 \text{ GeV} < \Gamma_{\text{top}} < 4.05 \text{ GeV}$ at 68% C.L.
- $\Gamma_{\text{top}} < 6.38 \text{ GeV}$ at 95% C.L.
Top quark Branching Ratio $B(t \rightarrow Wb) / B(t \rightarrow Wq)$

- Branching Ratio (BR) top decaying to bottom quark

$$R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{tb}|^2 + |V_{td}|^2}$$

- In the SM, $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$, $|V_{tb}| = 0.999146 \pm 0.000021$ - $0.000046$ (PDG : PRD 86, 010001 (2012))

- Comparison between observed data and expectations in 9 subsamples: $(ee, \mu\mu, e\mu) \ast 3$ b-tagging categories (0,1,2)

- BR is measured using the Maximum Likelihood estimator and the CKM Matrix element is extracted:

$$\mathcal{L} = \prod_i \mathcal{D} \left( \mu^i_{exp}(R, \sigma_{p\bar{p} \rightarrow t\bar{t}}, x_j) | N^i_{obs} \right) \prod_j G(x_j | 0, 1)$$

CDF Run II Preliminary, $\mathcal{L} = 8.7 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)}$</td>
<td>$0.87 \pm 0.07$</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
</tr>
</tbody>
</table>
Top Pair Production Cross Section

CDF results contribute to Tevatron combination by 60%.

Only CDF dilepton results used the full dataset.

\[
\begin{align*}
\text{CDF dilepton} & \quad 7.09 \pm 0.83 & \quad 8.8 \text{ fb}^{-1} \\
\text{CDF ANN lepton+jets} & \quad 7.82 \pm 0.56 & \quad 4.6 \text{ fb}^{-1} \\
\text{CDF SVX lepton+jets} & \quad 7.32 \pm 0.71 & \quad 4.6 \text{ fb}^{-1} \\
\text{CDF all-jets} & \quad 7.21 \pm 1.28 & \quad 2.9 \text{ fb}^{-1} \\
\text{CDF combined} & \quad 7.63 \pm 0.50 & \quad 5.4 \text{ fb}^{-1} \\
\text{DØ dilepton} & \quad 7.36 \pm 0.85 & \quad 5.3 \text{ fb}^{-1} \\
\text{DØ lepton+jets} & \quad 7.90 \pm 0.74 & \quad 5.3 \text{ fb}^{-1} \\
\text{DØ combined} & \quad 7.56 \pm 0.59 & \quad 5.3 \text{ fb}^{-1} \\
\text{Tevatron combined} \quad m_t = 172.5 \text{ GeV} & \quad 7.60 \pm 0.41 & \quad 8.8 \text{ fb}^{-1} \\
\end{align*}
\]

- Theoretical prediction (Precision \(\sim 4\%\))
  \[\sigma = 7.35^{+0.11}_{-0.21} \text{ (scales)}^{+0.17}_{-0.12} \text{ (PDF)}\]
- CDF combination (Precision \(\sim 6.5\%\))
  \[\sigma = 7.63 + 0.50 \text{ (stat+syst) pb}\]

\[\text{CDF} \rightarrow \bar{t}t \text{ cross section (pb) at } \sqrt{s} = 1.96 \text{ TeV}\]

Differential $d\sigma/d\cos\theta_t$ $t\bar{t}$ cross section

- Differential ttbar cross section, $d\sigma/d\cos\theta_t$ where $\theta_t$ is the angle between the top quark momentum and the incoming proton momentum as measured in the $t\bar{t}$ center-of-mass-frame.

- Characterize the shape of $d\sigma/d\cos\theta_t$ by expanding in the Legendre polynomials

$$\frac{d\sigma}{d\cos\theta_t} = \sum_{\ell} a_{\ell} P_{\ell}(\cos\theta_t)$$

- where $P_{\ell}$ is the Legendre polynomial of degree $\ell$, and $a_{\ell}$ is the Legendre moment of degree $\ell$.

\begin{table}
\begin{tabular}{|c|c|c|}
\hline
$\ell$ & $a_{\ell}$ (obs) & $a_{\ell}$ (pred) \\
\hline
1 & $0.40\pm0.12$ & $0.15^{+0.066}_{-0.065}$ \\
2 & $0.44\pm0.25$ & $0.28^{+0.083}_{-0.082}$ \\
3 & $0.11\pm0.21$ & $0.030^{+0.030}_{-0.014}$ \\
4 & $0.22\pm0.28$ & $0.035^{+0.016}_{-0.008}$ \\
5 & $0.11\pm0.33$ & $0.0048^{+0.001}_{-0.001}$ \\
6 & $0.24\pm0.40$ & $0.0060^{+0.002}_{-0.003}$ \\
7 & $-0.15\pm0.48$ & $-0.0028^{+0.001}_{-0.001}$ \\
8 & $0.16\pm0.65$ & $-0.0019^{+0.001}_{-0.003}$ \\
\hline
\end{tabular}
\end{table}

~2 $\sigma$ deviation from NLO prediction
Top $A_{FB}$ in Standard Model

✓ FB Asymmetry is defined by

$$A_{FB} = \frac{N_{\Delta y>0} - N_{\Delta y<0}}{N_{\Delta y>0} + N_{\Delta y<0}} \quad (\Delta y = y_t - y_{\bar{t}})$$

✓ Inclusive NLO prediction (QCD+EWK): $A_{FB} = 8.8 \pm 0.6\%$*
  
  
  o Terms of order $\alpha_s^3$ in the partonic cross section $d\sigma(q\bar{q} \rightarrow t\bar{t}X)$
  
  o Interference of the Born diagram with the 1-loop box and crossed box diagrams
  
  o Interference of initial and final state radiation

Positive asymmetry

Negative asymmetry

✓ Presence of new physics could make asymmetry
  
  o Axial vector exotic gluon $G'$ coupling
  
  o $Z'$ exchange, $W'$ interaction
  
  o Things to have to explain by BSM
    * Measured $t\bar{t}$ cross section ($\sigma$) and $d\sigma/dM_{t\bar{t}}$ are in good agreement with SM at Tevatron and LHC
    * Tiny $A_C$ at LHC and No other indications related to $A_{FB}$
Dependency checks of $t\bar{t}$ $A_{FB}$ in Lep+Jets events

- Observed $A_{FB} = 6.6 \pm 2.0\%$, **Parton-level** $A_{FB} = 16.4 \pm 4.7\%$ with 9.4 fb$^{-1}$.
- Mass and Rapidity dependence
  - Asymmetry linearly increases as a function of parton-level $M_{t\bar{t}}$ and $|\Delta y|$
  - Slopes are $3\sigma$ from zero and $\sim 2.3\sigma$ from SM prediction
- $p_T(t\bar{t})$ dependence
  - NLO (QCD+EW) $t\bar{t}$ + Background prediction agrees with data in top pair $p_T$ distribution
  - $A_{FB}$ in the background subtracted data depends on the $t\bar{t}$ $p_T$ spectrum
  - The normalized shapes from Powheg(NLO) and Pythia(LO) describes well data, but the total asymmetry are not
  - Reconstruction and modeling of the $p_T(t\bar{t})$ dependence of the asymmetry is robust, and that the excess asymmetry in the data is consistent with being independent of $p_T(t\bar{t})$
The generator-level distributions of $q_{\ell}\eta_{\ell}$ for different models are shown in the left plot. Shapes almost identical and a little shift of means.

The asymmetric part is decomposed from the $q_{\ell}\eta_{\ell}$ distribution at parton level with various physics models. $A(q_{\ell}\eta_{\ell})$ is parametrized with an functional form of $a \cdot \tanh \left( \frac{1}{2} \cdot q_{\ell}\eta_{\ell} \right)$.

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

Leptonic $A_{FB}$ kinematically correlated with top $A_{FB}$ and manifestation of $A_{FB}$ in the lepton from polarized tops.
• **Observed** $A_{FB}^{lep} = 9.4^{+3.2}_{-2.9}\%$ (SM Prediction: 3.8 ± 0.3%)

• The observed distribution of events vs $q_y\ell$ in the signal region (left) compared to the NLO QCD prediction of POWHEG and backgrounds

• The binned asymmetry $A_{FB}^{lep}(q_y\ell)$ after correcting for acceptance (right), compared to the NLO QCD prediction of POWHEG. The best fit for each is shown as the smooth curve of the same color. The dark (light) gray bands indicate the statistical (total) uncertainty on the fit curve to the data.
Leptonic Asymmetry in Dilepton channel

(a): Comparison of the observed number of leptons as a function of $q_\ell \eta_\ell$ with the SM expectations.

(b): Asymmetric part of the distribution from data with the best fit and the expectations from the powheg MC model. The bands indicate the one standard deviation uncertainty (statistical + systematic).

✓ Result:

$A_{lep}^{FB} = 7.2 \pm 5.2 \text{(stat)} \pm 3.0 \text{(syst)}\%$

$= 7.2 \pm 6.0\%$ (SM Prediction: $3.8 \pm 0.3\%$)

✓ Secondary result: $A_{FB}^{\Delta \eta}$ of $\Delta \eta$ between the two leptons in each event.

$A_{\Delta \eta}^{FB} = 7.6 \pm 7.2 \text{(stat)} \pm 3.9 \text{(syst)}\%$

$= 7.6 \pm 8.1\%$
CDF Combination of $t\bar{t}$ Leptonic $A_{FB}$

Accepted by PRL at last week!

- Combined the two measurements using BLUE method.
- Measurements in Lep+Jets channel using 3864 events, signal purity: 72.8%, at least one $b$-tagging:
  - $A_{lep FB}^{lep} = 9.4^{+3.2}_{-2.9} \%$
- Measurements in DIL channel using 569 events, signal purity: 71.8%, no $b$-tagging):
  - $A_{lep FB}^{lep} = 7.2 \pm 6.0 \%$
- Combined result:
  - $A_{lep FB}^{lep} = 9.0^{+2.8}_{-2.6} \%$
  (Weight: Lep+Jets 80%; DIL 20%. Correlation: 2.6%)
- Result is $2\sigma$ larger than NLO SM prediction:
  - (SM Prediction: $3.8 \pm 0.3 \%$)
**Forward-backward asymmetry in $b\bar{b}$ pairs**

- $A_{FB}$ in $b\bar{b}$ pairs at large $b\bar{b}$ mass using jet-triggered data and jet charge to identify $b$ from $\bar{b}$.
- The asymmetry is consistent with both zero and with the SM predictions as a function of $m(b\bar{b})$. And excluded a Axigluon model ($M_A = 200$ Gev/$c^2$). ([arXiv:1401.2443](http://arxiv.org/abs/1401.2443))
  - $A_{FB}$ only changes sign when $M_{Axigluon} > M(b\bar{b})$.
- CDF is working on $A_{FB}$ in $b\bar{b}$ pairs at low mass.
- More information in the CDF public page and public note 11092.

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Chang-Seong Moon, CNRS-Paris&INFN-Pisa  
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Conclusion

✓ Recent top quark pairs production and properties results from CDF are shown
   o Most measurements are consistent with the SM prediction.

✓ Top $A_{FB}$ still there at CDF
   o Many various experimental checks are done.
   o Inconsistent with SM calculation.
     • The Top asymmetry grows as a function of $t\bar{t}$ mass and rapidity
     • Leptonic asymmetry measurement show 2σ deviation from SM prediction.
   o Tevatron combination of $A_{FB}$ in progress.

✓ More information and results in the public webpage : CDF Top Groups and Tevatron Electroweak Working Group
   o http://www-cdf.fnal.gov/physics/new/top/top.html
   o http://tevewwg.fnal.gov