Top quark pair production and top quark properties at CDF

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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
Top quark properties

Any deviation from SM could indicate **New Physics** signal indirectly

- decay kinematics $t' \rightarrow Wq$ search
- $T \rightarrow tA_H$ search
- cross section resonance production
- $A_{FB}$
- single top, $V_{tb}$
- top mass width/lifetime
- top charge
- branching ratios
- FCNC $t \rightarrow H^+\bar{b}, t\chi$
- $W$ helicity spin correlation
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: $l\nu l\nu b\bar{b}$ (5%)
- Lepton+jets: $l\nu qq b\bar{b}$ (30%)
- All-hadronic: $qqqq b\bar{b}$ (45%)

<table>
<thead>
<tr>
<th>Top Pair Decay Channels</th>
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<tbody>
<tr>
<td>$t\bar{t}$</td>
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<tr>
<td>electron+jets</td>
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<tr>
<td>muon+jets</td>
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<tr>
<td>tau+jets</td>
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<tr>
<td>all-hadronic</td>
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<table>
<thead>
<tr>
<th>$t\bar{t}$</th>
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<tbody>
<tr>
<td>$e^+\mu^-$</td>
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<tr>
<td>$e^+\mu^+$</td>
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<tr>
<td>$e^+e^-$</td>
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<tr>
<td>$\tau^+$</td>
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<tr>
<td>$u\bar{d}$</td>
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<tr>
<td>$c\bar{s}$</td>
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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 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.

- $1.10$ GeV $< \Gamma_{\text{top}} < 4.05$ GeV at 68% C.L.
- $\Gamma_{\text{top}} < 6.38$ GeV at 95% C.L.
Top quark Branching Ratio $\text{BR}(t \to Wb) / \text{BR}(t \to Wq)$

- Branching Ratio (BR) top decaying to bottom quark

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

- In the SM, $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$, $|V_{tb}| = 0.999146^{+0.000021}_{-0.000046}$ [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:

$\mathcal{L} = \prod_i \mathcal{P}(\mu^i_{exp}(R, \sigma_{p\bar{p} \to tt}, x_j)|N_{obs}^i) \prod_j G(x_j|0, 1)$

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

<table>
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<tr>
<th>Parameter</th>
<th>Result</th>
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<tbody>
<tr>
<td>$R = \frac{\text{BR}(t \to Wb)}{\text{BR}(t \to Wq)}$</td>
<td>$0.87 \pm 0.07$</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
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Published in PRL at 2 Jun 2014
Top Pair Production Cross Section

CDF results contribute to 60% of Tevatron combination.

Only CDF dilepton results used the full dataset.

Theoretical prediction (Precision ~ 4%)
\[ \sigma = 7.35^{+0.11}_{-0.21} \text{ (scales)}^{+0.17}_{-0.12} \text{ (PDF)} \]

CDF combination (Precision ~ 6.5%)
\[ \sigma = 7.63 + 0.50 \text{ (stat+syst) pb} \]
Differential $d\sigma/d(\cos\theta_t)$ $t\bar{t}$ cross section

- Differential t-tbar 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

$$
\frac{d\sigma}{d(\cos\theta_t)} = \sum_{\ell=0}^{\infty} a_\ell P_\ell(\cos\theta_t)
$$

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

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

- Presence of new physics could make asymmetry
  - Axial vector exotic gluon $G'$ coupling
  - $Z'$ exchange, $W'$ interaction
  - 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 $A_{FB}$

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Dependency checks of $t\bar{t}$ $A_{FB}$ in Lep+Jets events

- Observed $A_{FB} = 6.3 \pm 1.9\%$, **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 $|\Delta y|$ and $M_{t\bar{t}}$.
  - Slopes are 2.8σ for $A_{FB}(|\Delta y|)$ and 2.4σ for $A_{FB}(M_{t\bar{t}})$ 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(1LO) and Pythia(LO) describes well data, but the total asymmetry are not.
  - The excess asymmetry in the data is consistent with being independent of $p_T(t\bar{t})$.


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Leptonic Asymmetry in $t\bar{t}$ Production

Leptonic asymmetry $A_{FB}^{\ell}$ kinematically correlated with the top quark pair asymmetry and the top quark polarization.

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 $a \cdot \tanh \left( \frac{1}{2} \cdot q_\ell \eta_\ell \right)$.

\[
A_{FB}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}
\]
Leptonic Asymmetry in Lep+Jets channel


- **Observed** $A_{lep}^{FB} = 9.4^{+3.2}_{-2.9}\%$ (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 $A_{lep}^{FB} (q_{y\ell})$ after correcting for acceptance (right), compared to the NLO QCD prediction of POWHEG. The best fit to the data points 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:

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

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

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

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

$= 7.6 \pm 8.1\%$

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arXiv:1404.3698

New
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:
- \( A_{\text{lep FB}}^{\text{L+J}} = 9.4^{+3.2}_{-2.9} \% \)

Measurements in DIL channel using 569 events, signal purity: 71.8%, no b-tagging:
- \( A_{\text{lep FB}}^{\text{DIL}} = 7.2 \pm 6.0 \% \)

Combined result:
- \( A_{\text{lep FB}} = 9.0^{+2.8}_{-2.6} \% \)

(Weight: Lep+Jets 80%; DIL 20%. Correlation: 2.6%)
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 $b$-quark from $\bar{b}$-quark.
- 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 ($M_A = 200 \text{ Gev/}c^2$). (JHEP 07 (2014) 005)
  - $A_{FB}$ only changes sign when $M_{Axigluon} > M_{b\bar{b}}$.
- CDF is working on $A_{FB}$ in $b\bar{b}$ pairs at low mass as well to confirm the results.
- More information in the CDF public page and public note 11092.
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 faster than the SM expectation as a function of $t\bar{t}$ mass and difference of $t\bar{t}$ rapidity.
    • Leptonic asymmetry measurement show $2\sigma$ deviation from SM prediction.
  o Tevatron combination of $A_{FB}$ in progress.

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