Top quark properties
(except for FB asymmetry, polarization, spin correlations, W helicity, mass)

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on behalf of

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The Top Quark

- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: $m_{\text{top}} \sim \text{gold atom}$
- large coupling to Higgs boson $\sim 1$: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25} \text{s} \ll \Lambda_{\text{QCD}}^{-1}$: decays before fragmenting
  $\rightarrow$ observe “naked” quark

$\Gamma_t = 1/\tau$

Is the top quark the particle as predicted by the SM?
Outline

Top quark decay branching ratios

Width and lifetime

Top quark couplings (FCNC)

Conclusions
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Top quark decay branching ratios

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Conclusions
Top quark couplings
Measurement of Branching Fractions

**Standard Model:**

\[ R_{SM} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 \approx 1 \]

beyond SM:

\[ R \neq 1 \]

e.g. decay into 4th generation quark: \( R < 1 \)
sensitive to b disappearance

\[ R = \frac{B(t \to Wb)}{B(t \to Wq)} \]

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\( V \) changes fractions of b-tagged jets:

DØ Run II

- 0 tag
- 1 tag
- ≥ 2 tags
Measurement of Branching Fractions

dilepton

topological information and b-tagging
Simultaneous Measurement of $\sigma$ and $R$

Maximize total Likelihood function simultaneously for branching ratio $R$ and top pair production cross section

\[ \sigma_{\text{tt}} = 7.74^{+0.67}_{-0.57} \text{ (stat+syst) pb} \]

\[ R = 0.90 \pm 0.04 \text{ (stat+syst)} \]

agrees with SM within 2.5\textsigma

using unitarity of CKM matrix:

\[ 0.90 < |V_{tb}| < 0.99 \text{ @ 95\% C.L.} \]

Outline

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Top Decay Width

- indirect determination (direct extraction not sensitive enough)

**t-channel cross section:**

\[ \sigma(t\text{-channel}) = 2.26 \pm 0.12 \text{ pb} \]

approximate NNNLO, \( m_t = 172.5 \text{ GeV} \)
Top Decay Width

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approximate NNNLO, \( m_t = 172.5 \text{ GeV} \)

**partial decay width:**

\[ \Gamma(t\rightarrow Wb) = 1.33 \text{ GeV} \]

NLO, \( m_t = 172.5 \text{ GeV} \)
Top Decay Width

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NLO, \( m_t = 172.5 \ 	ext{GeV} \)

- combine both measurements
- assume that coupling in top production and decay is the same

\[ \Gamma_t = \frac{\Gamma(t \to Wb)}{\beta(t \to Wb)} \]

\( \bar{t}t \) production
**Observation of t–Channel Production**

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t–channel
- measure t–channel and s–channel simultaneously


**observation with 5.5σ**

\[ \sigma(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59 \text{ pb} \]

\[ \sigma(\text{t-channel}) = 2.26 \pm 0.12 \text{ pb} \]

approximate NNNLO, \( m_t = 172.5 \text{ GeV} \)

\( m_t = 172.5 \text{ GeV} \)
**Top Decay Width**

**t-channel cross section:**

\[ \sigma(p\bar{p} \rightarrow t\bar{q}b + X) = 2.90 \pm 0.59 \text{ pb} \]

\[ \text{m.} = 172.5 \text{ GeV} \]

**partial decay width:**

\[ R = 0.90 \pm 0.04 \text{ (stat+syst)} \]

\[ \Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV} \]

\[ \tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25} \text{ s} \]

⇒ **most precise determination**

Phys. Rev. D84 012008 (2011)
**Top Decay Width**

**t-channel cross section:**

\[ \sigma(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59 \text{ pb} \]

\[ m_t = 172.5 \text{ GeV} \]

**partial decay width:**

\[ R = 0.90 \pm 0.04 \text{ (stat+syst)} \]

\[ |V_{tb}| > 0.81 \text{ at the 95\% C.L.} \]
Top Decay Width

**t-channel cross section:**

\[ \sigma(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59 \text{ pb} \]

\[ m_t = 172.5 \text{ GeV} \]

**partial decay width:**

\[ R = 0.90 \pm 0.04 \text{ (stat+syst)} \]

4th generation b' quark:

\[ m_{b'} > m_t - m_W \]

\[ |V_{td}|, |V_{ts}| \ll 1 \]

\[ |V_{tb'}|^2 = 1 - |V_{tb}|^2 \]

\[ |V_{tb}| > 0.81 \text{ at the 95\% C.L.} \]

\[ |V_{tb'}| < 0.59 \text{ at 95\% C.L.} \]
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Search for FCNC in Top Quark Decays

\[ \mathcal{L}_{\text{FCNC}} = \frac{e}{2 \sin \theta_W \cos \theta_W} \bar{t}\gamma_\mu (v_Z - a_Z \gamma_5) q Z^\mu + h.c. \]

- select 3 leptons, missing transverse momentum, 2 jets
Search for FCNC in Top Quark Decays

3 leptons + 0 jets

3 leptons + 1 jet

3 leptons + ≥2 jets
Search for FCNC in Top Quark Decays

B(\(t \rightarrow Zq\)) < 3.2% (3.8% expected)


95% C.L.
Excluded Regions by Colliders

LEP

\[ \gamma/\pi \]

Excluded at 95% C.L.

- $m_t = 175 \text{ GeV}$
- $\sigma_{t\bar{t}} = 6.90 \text{ pb}$
- $a_{\text{uZ}} = v_{\text{tcZ}} = a_{\text{tcZ}} = \kappa_{\text{tcZ}} = 0$

DØ, $L = 4.1 \text{ fb}^{-1}$

world's best limit

TEVATRON

\[ u,c \]

\[ \kappa_{\gamma/\pi} \]

\[ \kappa/\pi \]
Excluded Regions by Colliders

\[ m_t = 175 \text{ GeV}, \sigma_{\gamma} = 6.90 \text{ pb} \]
\[ a_{\gamma Z} = v_{\gamma Z} = a_{\gamma Z} = \kappa = 0 \]

DØ, \( L = 4.1 \text{ fb}^{-1} \)

arXiv:1206.0257
Outline

Top quark decay branching ratios
Width and lifetime
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## Conclusions: Top Quark Properties

- Top quark behaves as predicted by SM
- Many high precision measurements
- Competitive (mass) and complementary (spin correlations, FB asymmetry) to LHC

### Table: Top Quark Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Measurement</th>
<th>SM Prediction</th>
<th>Lumi (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{tt}$ (for $M_t = 172.5$ GeV)</td>
<td>$p\bar{p} \rightarrow t\bar{t}$</td>
<td>CDF: $7.5 \pm 0.31$(stat) $\pm 0.34$(syst) $\pm 0.15$(theory) pb  D0: $7.56_{-0.56}^{+0.63}$ (stat + syst + lumi) pb</td>
<td>$7.46_{-0.67}^{+0.45}$ pb</td>
</tr>
<tr>
<td>$\sigma_{tbq}$ (for $M_t = 172.5$ GeV)</td>
<td>$p\bar{p} \rightarrow t\bar{t}$</td>
<td>CDF: $0.8 \pm 0.4$ pb ($M_t = 175$ GeV)  D0: $2.90 \pm 0.59$ pb</td>
<td>$2.26 \pm 0.12$ pb</td>
</tr>
<tr>
<td>$\sigma_{tb}$ (for $M_t = 172.5$ GeV)</td>
<td>$p\bar{p} \rightarrow t\bar{t}$</td>
<td>CDF: $1.8_{-0.5}^{+0.7}$ pb ($M_t = 175$ GeV)  D0: $0.68_{-0.35}^{+0.38}$ pb</td>
<td>$1.04 \pm 0.04$ pb</td>
</tr>
<tr>
<td>$R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$</td>
<td></td>
<td>CDF: $&gt; 0.61$ @ 95% CL  D0: $0.90 \pm 0.04$</td>
<td>1</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
<td>$</td>
<td></td>
</tr>
<tr>
<td>$\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$</td>
<td>$p\bar{p} \rightarrow t\bar{t}$</td>
<td>CDF: $0.07_{-0.07}^{+0.15}$</td>
<td>0.18</td>
</tr>
<tr>
<td>$\sigma_{ttg}$ (for $M_t = 172.5$ GeV)</td>
<td>$p\bar{p} \rightarrow t\gamma$</td>
<td>CDF: $0.18 \pm 0.08$(stat + syst + lumi) pb</td>
<td>$0.17 \pm 0.03$ pb</td>
</tr>
<tr>
<td>$M_t$</td>
<td></td>
<td>Tev: $173.2 \pm 0.9$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>$M_t - M_t$</td>
<td></td>
<td>CDF: $-1.95 \pm 1.11$(stat) $\pm 0.59$(syst) GeV  D0: $0.8 \pm 1.8$(stat) $\pm 0.5$(syst) GeV</td>
<td>0</td>
</tr>
<tr>
<td>$W$ helicity fraction</td>
<td></td>
<td>Tev: $f_0 = 0.732 \pm 0.063$(stat) $\pm 0.052$(syst)</td>
<td>0.7</td>
</tr>
<tr>
<td>Charge</td>
<td></td>
<td>CDF: $-4/3$ excluded @ 95% CL  D0: $</td>
<td>q</td>
</tr>
<tr>
<td>$\Gamma_t$</td>
<td></td>
<td>CDF: $&lt; 7.6$ GeV @ 95% CL  D0: $1.99_{-0.55}^{+0.69}$ GeV</td>
<td>$1.26$ GeV</td>
</tr>
<tr>
<td>spin correlation</td>
<td>$p\bar{p} \rightarrow t\bar{t}$, beam</td>
<td>CDF: $0.72 \pm 0.64$(stat) $\pm 0.26$(syst)  D0: $0.66 \pm 0.23$(stat + sys)</td>
<td>$0.777_{-0.942}^{+0.027}$</td>
</tr>
<tr>
<td>Charge asymmetry</td>
<td>$p\bar{p} \rightarrow t\bar{t}$</td>
<td>CDF: $0.162 \pm 0.041$(stat) $\pm 0.022$(syst)  D0: $0.196 \pm 0.065$</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Top quark behaves as predicted by SM**
Backup
Top Quark Width

LO: \[ \Gamma_t^0 = \frac{G_F m_t^3}{8\pi\sqrt{2}} \]

NLO: \[ \Gamma_t = \Gamma_t^0 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right] \]

\[ \Gamma_t = 1.26 \text{ GeV for } m_t = 170 \text{ GeV} \]

CDF Conference
Note 10035

CDF: \[ \Gamma_t < 7.5 \text{ GeV} \]
(2-dimensional template fit)

⇒ model independent but not really sensitive
Sensitivity to New Physics (I)

**t-channel cross section:**

\[ p \rightarrow W^+ b \]

\[ \bar{p} \rightarrow W^- b \]

**Branching ratio B(t\rightarrow Wb):**

\[ \Gamma_t = \frac{\sigma(t\text{-channel}) \Gamma(t \rightarrow Wb)_{SM}}{\mathcal{B}(t \rightarrow Wb) \sigma(t\text{-channel})_{SM}} \]
### Combined Method

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{tt}$ [pb]</th>
<th>Offset [pb]</th>
<th>$+\sigma$ [pb]</th>
<th>$-\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical only</td>
<td>7.58</td>
<td></td>
<td>+0.24</td>
<td>-0.24</td>
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<tr>
<td>Muon identification</td>
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<td>+0.05</td>
<td></td>
<td>-0.05</td>
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<tr>
<td>Electron identification</td>
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<td>+0.12</td>
<td></td>
<td>-0.12</td>
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<tr>
<td>Triggers</td>
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<td>+0.09</td>
<td></td>
<td>-0.11</td>
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<tr>
<td>Background normalization</td>
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<td>+0.07</td>
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<td>-0.06</td>
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<tr>
<td>Signal modeling</td>
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<td>+0.23</td>
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<td>-0.21</td>
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<tr>
<td>$b$-tagging</td>
<td>-0.14</td>
<td>+0.12</td>
<td></td>
<td>-0.12</td>
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<tr>
<td>Monte Carlo statistics</td>
<td>-0.01</td>
<td>+0.06</td>
<td></td>
<td>-0.06</td>
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<tr>
<td>Fake background</td>
<td>-0.01</td>
<td>+0.06</td>
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<td>-0.04</td>
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<tr>
<td>$f_H$</td>
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<td>+0.02</td>
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<td>-0.02</td>
</tr>
<tr>
<td>Jet energy scale</td>
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<td>+0.00</td>
<td></td>
<td>-0.00</td>
</tr>
<tr>
<td>Jet reconstruction and identification</td>
<td>+0.18</td>
<td>+0.18</td>
<td></td>
<td>-0.17</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.12</td>
<td>+0.51</td>
<td></td>
<td>-0.44</td>
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<tr>
<td>Template statistics</td>
<td>+0.00</td>
<td>+0.03</td>
<td></td>
<td>-0.03</td>
</tr>
<tr>
<td>Other</td>
<td>+0.01</td>
<td>+0.14</td>
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<td>-0.13</td>
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<tr>
<td><strong>Total systematics</strong></td>
<td><strong>+0.65</strong></td>
<td></td>
<td></td>
<td><strong>-0.58</strong></td>
</tr>
<tr>
<td><strong>Fit result</strong></td>
<td><strong>7.78</strong></td>
<td></td>
<td>+0.77</td>
<td>-0.64</td>
</tr>
</tbody>
</table>

**$m_{top} = 172.5$ GeV**

**$\sigma_{tt} = 7.78^{+0.77}_{-0.64} \text{ (stat+syst+lumi)} \text{ pb}$**

**±9%**
Sensitivity to New Physics (I)

*example: charged Higgs with $m_{H^+} < m_t - m_b$*

**t-channel cross section:**

$$\Gamma_t = \frac{\sigma(t\text{-channel}) \, \Gamma(t \to Wb)_{\text{SM}}}{B(t \to Wb) \, \sigma(t\text{-channel})_{\text{SM}}}$$
Sensitivity to New Physics (I)

**Example:** charged Higgs with $m_{H^+} < m_t - m_b$

**t-channel cross section:**

\[
\Gamma_t = \frac{\sigma(t\text{-channel}) \cdot \Gamma(t \rightarrow Wb)_{SM}}{\mathcal{B}(t \rightarrow Wb) \cdot \sigma(t\text{-channel})_{SM}}
\]
Sensitivity to New Physics (II)

**example:** 4\(^{th}\) generation \(b'\) quark with \(m_{b'} > m_t - m_W\)

**t-channel cross section:**

\[
P \rightarrow W^+ b
\]

**branching ratio \(B(t \rightarrow Wb)\):**

\[
q \rightarrow \bar{q} W^- u \bar{b} \ell_- v
\]

Assume unitarity of the new 4x4 dimensional CKM matrix:

\[
|V_{tb}|^2 + |V_{tb'}|^2 = 1 \quad \text{and} \quad |V_{td}|, |V_{ts}| \text{ small}
\]

Using a flat prior for \(0 \leq |V_{tb}| \leq 1\)

\[
|V_{tb'}| < 0.59 \text{ at 95\% C.L.}
\]

*first such limit*
Top Pair Production Cross Sections

- good agreement with SM in all channels

- all channels measured except for $\tau_{\text{had}}$ combination: ±6%!