Heavy-Flavor Production at Accelerators

Nikolaos Kidonakis
(Kennesaw State University)

- QCD corrections and threshold resummation
- Top pair production at Tevatron and LHC
- Single top production at Tevatron and LHC
- Bottom and charm hadroproduction
QCD corrections and resummation

QCD corrections typically large for heavy quark production

NLO corrections fully known  Progress in NNLO corrections

Incomplete cancellations of infrared divergences between virtual diagrams and real diagrams with soft (low-energy) gluons

Soft corrections

\[
\ln^k \left( \frac{s_4/m^2}{s_4} \right)
\]

with \( k \leq 2n - 1 \) and \( s_4 \) distance from threshold

Soft-gluon corrections are dominant near threshold

Resum (exponentiate) these soft corrections

At NLL (NNLL) accuracy requires one-loop (two-loop) calculations in the eikonal approximation

Approximate NNLO cross section from expansion of resummed cross section

The hadronic cross section

\[
\sigma = \sum_f \int dx_1 dx_2 \ \phi_{f_1/p}(x_1, \mu_F) \ \phi_{f_2/\bar{p}}(x_2, \mu_F) \ \hat{\sigma}(s, t, u, \mu_F, \mu_R, \alpha_s)
\]
Top quark production

Dominant process is pair production $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$

Very good agreement of theory (with soft-gluon corrections) with Tevatron data

Recent evidence for single top production - cross section consistent with theory

Opportunities for study of electroweak properties of the top

Top quark mass value lowered from $\sim 175$ GeV to $\sim 172$ GeV
Top quark pair cross section at the Tevatron

\[
\sigma_{p \bar{p} \rightarrow t \bar{t}} \text{ at Tevatron } S^{1/2} = 1.96 \text{ TeV} \text{ MRST2006 pdf}
\]

\[
\sigma_{p \bar{p} \rightarrow t \bar{t}} \text{ at Tevatron } S^{1/2} = 1.96 \text{ TeV} \text{ CTEQ6.6 pdf}
\]

\[
\sigma_{\text{NNLOapprox}} (1.96 \text{ TeV}, m = 172 \text{ GeV}, \text{MRST}) = 7.80 \pm 0.31^{+0.03}_{-0.27}^{+0.23}_{-0.19} \text{ pb} = 7.80^{+0.39}_{-0.45} \text{ pb}
\]

\[
\sigma_{\text{NNLOapprox}} (1.96 \text{ TeV}, m = 172 \text{ GeV}, \text{CTEQ}) = 7.39 \pm 0.30^{+0.03}_{-0.20}^{+0.48}_{-0.37} \text{ pb} = 7.39^{+0.57}_{-0.52} \text{ pb}
\]

Kinematics uncertainty, scale variation, pdf errors

(NK, R. Vogt)
\begin{align*}
\text{CDF Run II Preliminary}^* & \quad \text{April 2008} \\
\text{Assume } m_t &= 175 \text{ GeV/c}^2 \\
\end{align*}

\begin{align*}
\text{DØ Run II preliminary}^* & \quad \text{March 2008} \\
\end{align*}

\begin{align*}
\text{l+jets (b-tagged and topological, PRL)} \\
910 \text{ pb}^{-1} & \\
7.42 \pm 0.53 \pm 0.46 \pm 0.45 \text{ pb} \\
\text{l+jets (from } B(t \to W_b)/B(t \to W_q), \text{ PRL)} \\
910 \text{ pb}^{-1} & \\
8.18 +0.90 & -0.84 \pm 0.50 \text{ pb} \\
\text{dilepton (topological)}^* \\
1050 \text{ pb}^{-1} & \\
6.8 +1.2 +0.9 & -1.1 -0.8 \pm 0.4 \text{ pb} \\
\text{l+track (b-tagged)}^* \\
1050 \text{ pb}^{-1} & \\
5.1 +1.6 +0.9 & -1.4 -0.8 \pm 0.3 \text{ pb} \\
\text{tau+lepton (b-tagged)}^* \\
1050 \text{ pb}^{-1} & \\
8.3 +2.0 +1.4 & -1.8 -1.2 \pm 0.5 \text{ pb} \\
\text{tau+jets (b-tagged)}^* \\
350 \text{ pb}^{-1} & \\
5.1 +4.3 +0.7 & -3.5 -0.7 \pm 0.3 \text{ pb} \\
\text{alljets (b-tagged, PRD)} \\
410 \text{ pb}^{-1} & \\
4.5 +2.0 +1.4 & -1.9 -1.1 \pm 0.3 \text{ pb} \\
\text{(stat) (syst) (lumi)} & \\
\end{align*}

\text{N. Kidonakis, PANIC 2008, Eilat, November 2008}
Experimental and theoretical uncertainties are of similar size
Top quark pair cross section at the LHC

\[ \sigma_{p p \rightarrow t \bar{t}}^{\text{NNLO approx}} (14 \text{ TeV}, m = 172 \text{ GeV}, \text{MRST}) = 968 \pm 4^{+79}_{-50}^{+12}_{-13} \text{ pb} = 968^{+80}_{-52} \text{ pb} \]

\[ \sigma_{p p \rightarrow t \bar{t}}^{\text{NNLO approx}} (14 \text{ TeV}, m = 172 \text{ GeV}, \text{CTEQ}) = 919 \pm 4^{+70}_{-45}^{+29}_{-31} \text{ pb} = 919^{+76}_{-55} \text{ pb} \]

Kinematics uncertainty, scale variation, pdf errors

(NK, R. Vogt)
Top quark $p_T$ distribution at Tevatron and LHC

$\bar{p}p \rightarrow t\bar{t}$

$S^{1/2} = 1.96$ TeV  $m = 175$ GeV

- NLO $\mu = m$
- NLO $\mu = m/2$
- NLO $\mu = 2m$
- NNLO 1PI $\mu = m$

$pp \rightarrow t\bar{t}$

$S^{1/2} = 14$ TeV  $m = 175$ GeV

- NLO $\mu = m$
- NLO $\mu = m/2$
- NLO $\mu = 2m$
- NNLO 1PI $\mu = m$
Single top quark production

Partonic processes at LO

(a) $t$ channel: $qb \rightarrow q't$ and $\bar{q}b \rightarrow \bar{q}'t$ ($ub \rightarrow dt$ and $\bar{d}b \rightarrow \bar{u}t$, etc.)

(b) $s$ channel: $q\bar{q}' \rightarrow \bar{b}t$ ($u\bar{d} \rightarrow \bar{b}t$, etc)

(c) associated $tW$ production: $bg \rightarrow tW^-$
One-loop eikonal vertex corrections to the soft function in the $t$ and $s$ channels

\[ q (\bar{q}) \quad q' (\bar{q}') \quad q (\bar{q}) \quad q' (\bar{q}') \]

\[ b \quad t \quad b \quad t \]

\[ q \quad \bar{b} \quad q \quad \bar{b} \]

\[ \bar{q}' \quad t \quad \bar{q}' \quad t \]
One-loop eikonal vertex corrections to the soft function in the $tW$ channel

Top-quark eikonal self-energy one-loop corrections: (a) $t$ channel; (b) $s$ channel; (c) associated $tW$ production
Single top production at the Tevatron - $t$ channel

Matched cross section (exact NLO + soft gluon corrections through NNNLO)

$$\sigma^{t\text{-channel}} (m_t = 170 \text{ GeV}) = 1.17^{+0.02}_{-0.01} \pm 0.06 \text{ pb} = 1.17 \pm 0.06 \text{ pb}$$

$$\sigma^{t\text{-channel}} (m_t = 175 \text{ GeV}) = 1.08^{+0.02}_{-0.01} \pm 0.06 \text{ pb} = 1.08 \pm 0.06 \text{ pb}$$

Cross section for anti-top production is identical
Single top production at the Tevatron - $s$ channel

Matched cross section (exact NLO + soft gluon corrections through NNNLO)

$\sigma^{s\text{-channel}}(m_t = 170 \text{ GeV}) = 0.56 \pm 0.02 \pm 0.01 \text{ pb} = 0.56 \pm 0.03 \text{ pb}$

$\sigma^{s\text{-channel}}(m_t = 175 \text{ GeV}) = 0.49 \pm 0.02 \pm 0.01 \text{ pb} = 0.49 \pm 0.02 \text{ pb}$

Cross section for anti-top production is identical
Single top production at the Tevatron - $tW$ channel

Approximate NNNLO cross section

$$\sigma^{tW}(m_t = 170\text{GeV}) = 0.15 \pm 0.02 \pm 0.03\text{ pb} = 0.15 \pm 0.03\text{ pb}$$

$$\sigma^{tW}(m_t = 175\text{GeV}) = 0.13 \pm 0.02 \pm 0.02\text{ pb} = 0.13 \pm 0.03\text{ pb}$$

Cross section for anti-top production is identical
DØ Run II 0.9 fb⁻¹  

March 2008

<table>
<thead>
<tr>
<th>Method</th>
<th>σ (pT bar → tb+X, tqb+X) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Trees</td>
<td>4.9 ±1.4 −1.4</td>
</tr>
<tr>
<td>Matrix Elements</td>
<td>4.8 ±1.6 −1.4</td>
</tr>
<tr>
<td>Bayesian NNs</td>
<td>4.4 ±1.6 −1.4</td>
</tr>
<tr>
<td>Combination</td>
<td>4.7 ±1.3 −1.3</td>
</tr>
</tbody>
</table>

CDF and DØ tb+tqb Cross Section

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</thead>
<tbody>
<tr>
<td>CDF Decision Trees 2.7 fb⁻¹</td>
<td>2.4 ±0.8 −0.7</td>
</tr>
<tr>
<td>CDF Matrix Elements 2.7 fb⁻¹</td>
<td>2.7 ±0.8 −0.7</td>
</tr>
<tr>
<td>CDF Neural Networks 2.7 fb⁻¹</td>
<td>2.1 ±0.7 −0.6</td>
</tr>
<tr>
<td>CDF Likelihood Funcs. 2.7 fb⁻¹</td>
<td>2.0 ±0.9 −0.8</td>
</tr>
<tr>
<td>CDF Combination 2.2 fb⁻¹ preliminary</td>
<td>2.2 ±0.7 −0.7</td>
</tr>
<tr>
<td>DØ Decision Trees 0.9 fb⁻¹</td>
<td>4.9 ±1.4 −1.4</td>
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</tr>
<tr>
<td>DØ Combination PRD</td>
<td>4.7 ±1.3 −1.3</td>
</tr>
</tbody>
</table>

N. Kidonakis, PRD 74, 114012 (2006) m_t = 175 GeV

July 2008

σ (pT bar → tb+X, tqb+X) [pb]
Single top production at the LHC - $t$ channel

Threshold corrections not a good approximation of full QCD corrections

Exact NLO cross section

$$\sigma^{t\text{-channel}}_{\text{top}} (m_t = 170 \text{ GeV}) = 152 \pm 5 \pm 3 \text{ pb} = 152 \pm 6 \text{ pb}$$

↑↑

scale pdf

$$\sigma^{t\text{-channel}}_{\text{top}} (m_t = 175 \text{ GeV}) = 146 \pm 4 \pm 3 \text{ pb} = 146 \pm 5 \text{ pb}$$

↑↑

scale pdf

Antitop production at the LHC - $t$ channel

Exact NLO cross section

$$\sigma^{t\text{-channel}}_{\text{antitop}} (m_t = 170 \text{ GeV}) = 93 \pm 3 \pm 2 \text{ pb} = 93 \pm 4 \text{ pb}$$

↑↑

scale pdf

$$\sigma^{t\text{-channel}}_{\text{antitop}} (m_t = 175 \text{ GeV}) = 89 \pm 3 \pm 2 \text{ pb} = 89 \pm 4 \text{ pb}$$

↑↑

scale pdf
Single top production at the LHC - $s$ channel

Matched cross section (exact NLO + soft gluon corrections through NNNLO)

$$\sigma_{\text{top}}^{s-\text{channel}}(m_t = 170\text{ GeV}) = 8.0^{+0.6}_{-0.5} \pm 0.1\text{ pb} = 8.0^{+0.6}_{-0.5}\text{ pb}$$

$\uparrow$ scale $\uparrow$ pdf

$$\sigma_{\text{top}}^{s-\text{channel}}(m_t = 175\text{ GeV}) = 7.2^{+0.6}_{-0.5} \pm 0.1\text{ pb} = 7.2^{+0.6}_{-0.5}\text{ pb}$$

$\uparrow$ scale $\uparrow$ pdf
Single antitop production at the LHC - $s$ channel

Matched cross section (exact NLO + soft gluon corrections through NNNLO)

$$\sigma_{antitop}^{s-channel}(m_t = 170 \text{GeV}) = 4.5 \pm 0.1 \pm 0.1 \text{ pb} = 4.5 \pm 0.2 \text{ pb}$$

$$\uparrow \quad \uparrow$$

scale \quad pdf

$$\sigma_{antitop}^{s-channel}(m_t = 175 \text{GeV}) = 4.0 \pm 0.1 \pm 0.1 \text{ pb} = 4.0 \pm 0.2 \text{ pb}$$

$$\uparrow \quad \uparrow$$

scale \quad pdf
Single top production at the LHC - $tW$ channel

Matched cross section (exact NLO + soft gluon corrections through NNNLO)

$$\sigma^{tW}(m_t = 170 \text{ GeV}) = 44 \pm 5 \pm 1 \text{ pb} = 44 \pm 5 \text{ pb}$$

$$\sigma^{tW}(m_t = 175 \text{ GeV}) = 41 \pm 4 \pm 1 \text{ pb} = 41 \pm 4 \text{ pb}$$

Cross section for anti-top production is identical
Bottom quark pair hadroproduction

\[ gg \quad q\bar{q} \quad gg + q\bar{q} \quad m = 4.75 \text{ GeV} \]

Threshold approximation better in 1PI kinematics

nk, r. voge
\( \sigma(pp \to \bar{b}b) \text{[nb]} \)

- (a) \( \mu = \frac{m}{2} \)
- (b) \( \mu = m \)
- (c) \( \mu = 2m \)

\( \sqrt{S} \text{[GeV]} \)

- NLO
- NNLO-NNLL
- NNLO-NNLL+\( \zeta \)

\( m = 4.75 \text{ GeV} \)

\( m = 4.5 \text{ GeV} \)

\( m = 5 \text{ GeV} \)

NK, R. Vogt

N. Kidonakis, PANIC 2008, Eilat, November 2008
$b\bar{b}$ production

Scale dependence and $p_T$ distribution for HERA-B energy

N. Kidonakis, PANIC 2008, Eilat, November 2008
Large uncertainties but data agrees with theory
Charm quark pair hadroproduction

Threshold approximation better in 1PI kinematics

NK, R. Vogt

N. Kidonakis, PANIC 2008, Eilat, November 2008
NLO ———— NNLO-NNLL - - - - - - - NNLO-NNNLL+ζ - - - - - - -

(a,b) \( m = 1.2 \text{ GeV} \)  \( (c,d) \) \( m = 1.5 \text{ GeV} \)  \( (e,f) \) \( m = 1.8 \text{ GeV} \)
Two-loop soft-gluon resummation for heavy quarks

plus self-energy and counterterm diagrams

Calculation of two-loop soft anomalous dimension N.K., P. Stephens

Eikonal approximation – Isolate UV poles in dimensional regularization

For massless quarks $\Gamma_S^{(2)} = \frac{K}{2} \Gamma_S^{(1)}$ Aybat, Dixon, Sterman

with $K = C_A \left( \frac{67}{18} - \frac{\pi^2}{6} \right) - \frac{5n_f}{9}$ Kodaira, Trentadue

Found that $n_f$ terms for massive case obey above relation - work in progress for $C_A$ terms

This will allow NNLL resummation
Summary and Outlook

- Top pair and single top production at the Tevatron
- Data agrees with theory - uncertainties of similar size
- LHC - top quark factory
- Increased accuracy for top cross section and mass
- Bottom and charm hadroproduction - larger uncertainties
- Theoretical progress in higher-order QCD corrections