Electroweak corrections to heavy quark and di-jet production

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Outline

• Motivation
• Next-to-leading order corrections $O(\alpha^2_s\alpha)$
• Results & Discussion
• Conclusion
**Why weak effects in hadronic collisions?**

- **Hadron Colliders**
  - Provide high energy events
  - Many observables will be measured at 10-20% accuracy

**Theory: NLO corrections**

- **QCD-corrections** are dominant
- **Electroweak corrections**
  - Smaller coupling: $\alpha < \alpha_s$
  - Large logarithms: Sudakov logarithms
    \[ \ln^2 \left( \frac{E_{cm}}{M_w} \right), \ln \left( \frac{E_{cm}}{M_w} \right) \]

(Sudakov 1954)
(Kühn, Penin, Smirnov 1999)
(Ciabattoni, Comelli 1999)
(Denner, Pozzorini 2001)
Origin of the Sudakov logarithms

- Analogy to QCD and QED
- Soft and collinear logarithms in virtual corrections
- Cancellation in the sum of virtual and real contributions
  - (Bloch, Nordsieck 1937)
  - (Kinoshita, Lee, Nauenberg 1964)

Weak theory: massive bosons ($Z$, $W$)

Virtual and real corrections can be separated
Top-quark pair production

- Top-quark \( m_{\text{top}} \approx 173 \text{ GeV} \)
  - Still not very well measured
  - Probes physics at high mass scale
  - Plays central role in many SM extensions

- \( t\bar{t} \)-production at Hadron Colliders
Top-quark pair production

- Experimentally (e.g. $p + \bar{p} \rightarrow t\bar{t} \rightarrow b\bar{b} + l\bar{l} + j j$)
- Decay channels: di-lepton, semi-leptonic, full hadronic
- Tevatron: $\frac{\Delta m_t}{m_t} \sim 1\%$
- Leading order $p_T$ distribution
Bottom jet production

- Bottom-quark ($m_b = 0$)
  - Background process (e.g. $t\bar{t}, t\bar{t} + H$)
  - Testing the SM at high $p_T$
  - New physics: e.g. $\tilde{g}$-production

- $b$-jet production at Hadron Colliders

\[
\begin{align*}
  b & \rightarrow b \\
  q & \rightarrow q
\end{align*}
\]

\[
\begin{align*}
  g & \rightarrow g \\
  b & \rightarrow b
\end{align*}
\]

\[
\begin{align*}
  q & \rightarrow q \\
  Z, \gamma & \\
  b & \rightarrow b
\end{align*}
\]
Bottom jet production

- QCD, Mixed and Electroweak contributions

<table>
<thead>
<tr>
<th>initial state</th>
<th>single $b$-tag</th>
<th>double $b$-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark-induced</td>
<td>$qb \rightarrow qb$, $q\bar{b} \rightarrow q\bar{b}$, $\bar{q}b \rightarrow \bar{q}b$, $\bar{q}\bar{b} \rightarrow \bar{q}\bar{b}$</td>
<td>$q\bar{q} \rightarrow b\bar{b}$</td>
</tr>
<tr>
<td>gluon-induced</td>
<td>$gb \rightarrow gb$, $g\bar{b} \rightarrow g\bar{b}$</td>
<td>$gg \rightarrow b\bar{b}$</td>
</tr>
<tr>
<td>pure bottom-induced</td>
<td>$b\bar{b} \rightarrow b\bar{b}$, $bb \rightarrow bb$, $\bar{b}\bar{b} \rightarrow \bar{b}\bar{b}$</td>
<td></td>
</tr>
</tbody>
</table>

- Experimentally
  - Lifetime of $B$ mesons $\sim 1.5 \times 10^{-12}s$
  - Displaced tracks allow $b$-jet identification
Bottom jet production

- $p_T$ distributions at leading order and their composition.
**Di-jet production**

- Gluon- & light quark-jets \((m_u = m_d = m_s = m_c = 0)\)
  - Fundamental Test of QCD
  - Major background for many SM processes
  - New physics search, e.g. \(Z'\)

- Di-jet production at Hadron Colliders

<table>
<thead>
<tr>
<th>Processes with external Gluons</th>
<th>(\alpha_S^2)</th>
<th>(\alpha_S\alpha)</th>
<th>(\alpha_s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(gg \rightarrow gg, gg \rightarrow q\bar{q}, gq \rightarrow gq, g\bar{q} \rightarrow g\bar{q}, q\bar{q} \rightarrow gg)</td>
<td>✓</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processes with external Quarks only</th>
<th>(\alpha_S^2)</th>
<th>(\alpha_S\alpha)</th>
<th>(\alpha_s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q\bar{q} \rightarrow q'\bar{q}', q\bar{q}' \rightarrow q\bar{q}', qq' \rightarrow q\bar{q}', \bar{q}'\bar{q} \rightarrow q'q\bar{q})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(q\bar{q} \rightarrow q\bar{q}, qq \rightarrow qq, \bar{q}\bar{q} \rightarrow \bar{q}\bar{q})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
**Di-jet production**

- Results from the Tevatron
  
  - In agreement with NLO QCD prediction


**Data**

- $|y^{jet1,2}| < 1$, $L_{ee} = 1.13$ fb$^{-1}$

**NLO: NLOJET++, CTEQ6.1M corrected to hadron level**

$\mu = p_{T}^{\text{mean}}(\text{jet1,2})/2$, $R_{\text{sep}}=1.3$

**Systematic uncertainties**

**CDF Run II Preliminary**

![Graph showing di-jet production results](image-url)
Di-jet production

- Results from the Tevatron (T. Aaltonen et al [CDF Collaboration] 2008)
- Search for New Physics

![Graph showing 95% C.L. limits for different particles](image)

- $W'$
- $Z'$
- RS graviton
- $q$ Axigluon/Coloron
- $E_d$ diquark

Mass [GeV/c^2]
Di-jet production

- LHC: Di-jet-Masses up to several TeV
- $p_T$ distribution at leading order

![Graph showing di-jet production at LHC with distributions for QCD and Electroweak processes.]
Luminosity at the LHC

• Consider top-quark pair production at LO

• Define luminosity function:

\[ L_{ij}(\tau, \mu_F) = \frac{1}{S} \int_{\tau}^{1} dx_1 \frac{1}{x_1} f_{i,p}(x_1, \mu_F) f_{j,p}(\frac{\tau}{x_1}, \mu_F) \text{ with } \tau = \frac{E_{cm}^2}{S} \]

• Similar for \( b \)-jet and di-jet production!
Status of NLO calculations

• Top-quark pair production
  • QCD corrections $O(\alpha_s^3)$
  • (Electro-)weak corrections $O(\alpha_s^2\alpha)$

• $b$-jet production
  • QCD corrections $O(\alpha_s^3)$
  • Electroweak corrections $O(\alpha_s^2\alpha)$

• Di-jet production
  • QCD corrections $O(\alpha_s^3)$
  • Electroweak corrections $O(\alpha_s^2\alpha)$

(Dawson, Nason, Ellis 1988)
(Beenakker, Kuijf, Neerven, Smith 1989)
(Bernreuther, Brandenburg, Si, Uwer 2004)
(Melnikov, Schulze 2009)
(Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth 1994)
(Bernreuther, Fücker, Si 2005, 2006)
(Kühn, A.S., Uwer 2005, 2006)
(Hollik, Kollar 2007)
(Dawson, Ellis, Nason 1988)
(Beenakker, Kuijf, Neerven, Smith 1989)
(Frixione, Mangano 1997)
(Moretti et al 2003)
(Kühn, A.S., Uwer 2009)
(Ellis, Sexton 1985)
(Aversa et al 1988, 1991)
(Moretti et al 2006)
General Remarks

• Corrections of $O(\alpha_s^2 \alpha)$ calculated in Feynman-’t Hooft Gauge

• Consider only weak corrections → neglecting photonic contributions
  • Gauge invariant subset
  • Photonic contributions involve no Sudakov logarithms

• $t\bar{t}$ and $b$-jet production
  • $O(\alpha)$ corrections to LO $\alpha_s^2$ processes: $Z, W, \phi, (\chi, H)$

• Di-jet production
  • $O(\alpha)$ corrections to LO $\alpha_s^2$ processes: $Z, W$
  • $O(\alpha_s)$ corrections to LO $\alpha_s \alpha$ processes
Methods: Overview

- Passarino-Veltman reduction
- Scalar Integrals
- Renormalisation
- Real corrections
Methods: Renormalisation

- Renormalisation: Counterterm formalism (Hollik, Böhm, Spiesberger 1984) (Denner 1991)

\[ \mathcal{L}(\Psi_0, A_0, m_0, g_0) \rightarrow \mathcal{L}(\Psi_R, A_R, m_R, g_R) + \mathcal{L}_{ct}(\Psi_R, A_R, m_R, g_R) \]

- \( t\bar{t} \) and \( b \)-jet production: \( O(\alpha) \) corrections
  - On-shell scheme
  - No coupling renormalisation is needed
  - Only wave function and mass renormalisation

- Di-jet production
  - On-shell scheme (like \( t\bar{t} \) and \( b \)-jet)
  - \( \overline{\text{MS}} \) scheme
Methods: Real corrections

- IR singularities
  - Phase-space-slicing ✓
  - (Dipole-) subtraction method ✓

- Virtual corrections considered here
  - Only four quark processes are IR divergent

- IR divergent real corrections to four quark processes
  - Only $q(\bar{q}) \rightarrow q(\bar{q}) + g$ splitting must be considered

- $t\bar{t}$ and $b$-jet production
  - Partonic results are independent from $\mu_F$
Consistency

• $t\bar{t}$ production
  • Independent calculation by Peter Uwer ✓
  • Parallel work ✓
  • Literature ✓

• $b$-jet production
  • Crossing symmetries ✓
  • Double $b$-tag: Comparison with massive calculation ✓
  • Comparison between dipole-subtraction and phase-space-slicing ✓

• Di-jet production
  • Cross checks in progress ... (✓)
Consistency

- $b$-jet production: Slicing vs. subtraction method
- Comparison in standard deviations

\[
\frac{\frac{d\sigma_{\text{Dipole}}}{dp_T}}{(\sigma^2_{\text{Dipole}} + \sigma^2_{\text{Slicing}})^{0.5}} - \frac{d\sigma_{\text{Slicing}}}{dp_T}
\]

Channel: $qq \rightarrow bb$
Channel: $qb \rightarrow q\bar{b} + q\bar{b} \rightarrow \bar{q}b$
Channel: $qb \rightarrow q\bar{b} + q\bar{b} \rightarrow \bar{q}b$

$p_T$ [GeV]
Example

- Real corrections for $q\bar{q} \rightarrow b\bar{b}g$

$$\frac{1}{4N^2} \sum_{\text{Spin}} \sum_{\text{Colour}} |M^{q\bar{q} \rightarrow b\bar{b}g}|^2 = \alpha_s^2 \alpha(4\pi)^3 \frac{N^2 - 1}{N^2}$$

$$\times \left( g_v^q g_v^b (t_1^2 + t_2^2 + u_1^2 + u_2^2) - g_d^q g_d^b (t_1^2 + t_2^2 - u_1^2 - u_2^2) \right)$$

$$\times \frac{1}{s} \frac{1}{s - m_Z^2} \frac{1}{s + t_1 + t_2 + u_1 + u_2} \frac{1}{s + t_1 + t_2 + u_1 + u_2 + m_Z^2}$$

$$\times \left( 2s^2 + (t_1 + t_2 + u_1 + u_2)(2s - m_Z^2) \right)$$

$$\times \left( (t_1 + t_2 - u_1 - u_2)s^2 + ((t_1 + t_2)^2 - (u_1 + u_2)^2)s \right)$$

$$+ (t_1 + t_2 + u_1 + u_2)(t_1 t_2 - u_1 u_2)$$
Partonic results for $t\bar{t}$ production

- Quark-induced processes receive larger corrections
Total hadronic cross section for $t\bar{t}$

- Small corrections

**TEVATRON**

**LHC**

![Graphs showing relative weak corrections for $t\bar{t}$ production](image-url)

- $M_h = 120$ GeV
- $M_h = 200$ GeV
- $M_h = 1000$ GeV

$m_t$ [GeV]
**$t\bar{t}$ production at the LHC**

- Relative corrections to $M_{t\bar{t}} = \sqrt{(k_t + k_{\bar{t}})^2}$

\[
\frac{d\sigma_{NLO}}{dM_{tt}} \bigg/ \frac{d\sigma_{LO}}{dM_{tt}} \quad [\%]
\]

- \(M_h = 1000\) GeV
- \(M_h = 120\) GeV
$t\bar{t}$ production at the LHC

- Relative corrections to $p_T$
$t\bar{t}$ production at the Tevatron

- Relative corrections

![Graphs showing relative corrections](image-url)
**b-jet production at the LHC**

- Relative corrections to $p_T$: double $b$ tag
**b-jet production at the LHC**

- Comparison with massive results: double $b$-tag

![Graph showing double $b$-tag production at the LHC](image)

- $m_b = 4.82$ GeV
- $m_b = 0$
*b*-jet production at the LHC

- Relative corrections to $p_T$: single $b$ tag

![Graph showing relative corrections to $p_T$ for single $b$ tag at the LHC](image)
b-jet production at the LHC

- Relative corrections to $p_T$:

![Graphs showing relative corrections to $p_T$ for single and double b-tag at LHC at 10 TeV.](image-url)
• Relative corrections to $p_T$

**Double b-tag**

**Single b-tag**
Di-jet production at the LHC

- Preliminary Result

\[
\frac{d\sigma_{\text{NLO}}}{dp_T} / \frac{d\sigma_{\text{LO}}}{dp_T} \quad [\%]
\]

\( p_T \quad [\text{GeV}] \)
Discussion: General remarks

• Important corrections for differential distributions at high energies
  • Statistics ?

• Parton distribution functions
  • Error for light quark-PDF’s \( \sim 10\% \) (2 TeV)
  • Error for gluon-PDF’s \( \sim 50\% \) (2 TeV)

• Other systematics: Uncertainty on jet energy scale, ...

• Weak boson emission ?

(Baur 2006)
Discussion: $t\bar{t}$-production

- Total cross section
  - Experiment: $\frac{\Delta \sigma}{\sigma} \approx 10(5)\%$
  - Theory: Heading to NNLO $O(\alpha_s^4)$ accuracy

$\rightarrow$ Electroweak corrections $\frac{\sigma(\alpha \alpha_s^2)}{\sigma(\alpha_s^2)} \approx 2\%$ become relevant

- Differential Distributions
  - Impact of weak corrections is $\approx 15\text{-}20\%$
  - Should be considered for search for New Physics
Discussion:  $b$-jet production

- Sudakov logarithms become relevant at high energies
- Experiment
  - $b$-tagging at high transverse momenta?
  - Efficiencies, Mistags, ...?
**Discussion: $b$-jet production**

- Sudakov logarithms become relevant at high energies
- Experiment
  - $b$-tagging at high transverse momenta?
  - Efficencies, Mistags, ... ?

![Graph showing cross-section uncertainty as a function of $B$ tagged jet $P_T$ (GeV/c)]

- Statistic error
- Systematic error
- Sum

(CMS NOTE 2006/120)
Conclusion

- Heavy quark and di-jet production
  - Standard Model?
  - New physics?

- Analytic results

- Electroweak corrections have impact on differential distributions at the LHC
  - Top-quark pair production: 15 – 20%
  - $b$-jet production: 10 – 15%
  - di-jet production (preliminary): $\sim 10\%$