Top Pair Production with a Jet with NLO QCD Off-Shell Effects

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Plan

- Motivation for $ttj$ production at the LHC
- Motivation for top-quark off-shell effects based on $tt$ production
- Complete off-shell effects with HELAC-NLO for $ttj$
- Results for LHC @ 8 TeV
- Summary & Outlook

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@ LHC tops are produced with large energies & high transverse momenta
- Increase probability for additional (hard) radiation of gluons $\rightarrow ttj$ final state
- How big is the contribution of $ttj$ in the inclusive $tt$ sample?

- NNLO $tt$ cross section for $m_t = 173.2$ GeV @ LHC$_{13\text{ TeV}}$ with CT14 PDF set:

$$\sigma(tt) = 807 \text{ pb}$$

| Jet $p_T$ cut [GeV] | $\sigma(ttj)$ [pb]          | $\sigma(ttj)/\sigma(tt)$ [%] |
|---------------------|-----------------------------|-----------------------------|
| 40                  | $296.97 \pm 0.29$           | 37                          |
| 60                  | $207.88 \pm 0.19$           | 26                          |
| 80                  | $152.89 \pm 0.13$           | 19                          |
| 100                 | $115.60 \pm 0.14$           | 14                          |
| 120                 | $89.05 \pm 0.10$            | 11                          |

*TOP++, Czakon, Mitov ‘14*

*HELAC-NLO, G. Bevilacqua et al., ‘13*
**ttj Process**

- Background for SM Higgs production in VBF: \( qq \rightarrow H qq \rightarrow WW qq \)
- 2 tagging jets: \( \Delta y_{jj} = |y_{j1} - y_{j2}| > 4 \) \& \( y_{j1} \times y_{j2} < 0 \)
- \( \downarrow \) tt background: \( tt \rightarrow WWbb \) \& \( \uparrow \) ttj background: \( ttj \rightarrow WWbbj \)
Off-Shell Effects

- Larger impact on differential distributions
- Full NWA (tt) versus full calculation (WWbb) for $p_T(bb)$

- Controlled by the ratio $\Gamma_t/m_t \approx 10^{-2}$
- For $\sigma_{tot}$ at few % level (tt, ttj & ttH)

A. Denner et al. '11, '12, '15
G. Bevilacqua et al. '11, '16
R. Frederix '14
F. Cascioli et al. '14
G. Heinrich et al '14

A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12
Off-Shell Effects for $tt$

- Full NWA ($tt$) versus full calculation ($WWbb$) for $M_{e+b}$

- If both top and W decay on-shell $\rightarrow$ end-point given by sharp cut

$$M_{\ell b} = \sqrt{m_t^2 - m_W^2} \approx 152 \text{ GeV}$$

- Additional radiation & off-shell effects introduce smearing

\[\frac{d\sigma}{dM_{e+b}} \quad \text{[fb/GeV]}\]

\[pp \rightarrow \nu_e e^+ \mu^- \bar{\nu}_\mu b \bar{b} + X\]

$\sqrt{s} = 7 \text{ TeV}$

\[\frac{t\bar{t}}{WWb\bar{b}} - 1 \quad [\%]\]
Off-Shell Effects for $ttj$

$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$

- $ttj$ with leptonic decays at $\mathcal{O}(\alpha_s^4\alpha^4)$
- 2 $\rightarrow$ 5 process from the QCD point of view
- Diagrams with complete off-shell effects for top & W gauge boson for $gg$ initial state:
  - **LO**: 508
  - **Real emission**: 4447
Off-Shell Effects for $ttj$

- $gg$ channel comprises 39,180 one-loop diagrams → according to QGRAF
  
  P. Nogueira ‘93

- The most complicated ones are 1155 hexagons & 120 heptagons
- Tensor integrals up to rank six

NWA for $ttj$ (on-shell top-quark production) – up to pentagons!

Full calculations for $ttj$ – up to heptagons!
Intermediate Top Resonances

- Putting simply $\Gamma_t \neq 0$ violates gauge invariance
- Gauge-invariant treatment $\rightarrow$ complex-mass scheme
- $\Gamma_t$ incorporated into top mass via:
  \begin{equation}
  \mu_t^2 = m_t^2 - i m_t \Gamma_t
  \end{equation}

- All matrix elements evaluated using complex masses
- $\mu_t^2$ identified with the position of pole of top-quark propagator
- Top-mass counter-term $\delta \mu_t$ related to top-quark self-energy at: $p_t^2 = \mu_t^2$

- *Another non trivial aspect:* evaluation of one-loop scalar integrals in presence of complex masses!
- Scalar integrals with complex masses $\rightarrow$ supported e.g. by **ONELOOP**

A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99
A. Denner, S. Dittmaier, M. Roth, L. H. Wieders '05
A. van Hameren '11
Off-Shell Effects for $ttj$

\[ pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}j + X \]

- Different lepton generations $\to$ to avoid virtual photon singularities $\gamma \to ll$
- Effects at the level of 0.5% $\to$ checked @ LO
- Diagrams for gg initial state @ LO: 508 for $e^+\mu^- \to 1240$ for $e^+e^-$
- SM Parameters in $G_\mu$ scheme:

| Parameter | Value |
|-----------|-------|
| $G_F$     | $1.16637 \cdot 10^{-5}$ GeV$^{-2}$ |
| $m_t$     | 173.3 GeV |
| $m_W$     | 80.399 GeV |
| $m_Z$     | 91.1876 GeV |
| $\Gamma_W$ | 2.09974 GeV |
| $\Gamma_Z$ | 2.50966 GeV |
| $\Gamma_t^{LO}$ | 1.48132 GeV |
| $\Gamma_t^{NLO}$ | 1.3542 GeV |

- MSTW2008 set of PDF & $\mu_R = \mu_F = \mu_0 = m_t$
- All light quarks including $b$-quarks and leptons are massless
- Suppressed contribution from $b$ quarks in the initial state neglected
- Amounts to 0.8% @ LO
Top Width for Unstable W Bosons

- Finite W width contributions included in matrix elements & in $\Gamma_t$
- Top width for unstable W bosons, neglecting bottom quark mass @ LO & NLO

\[
\Gamma_t^{LO} = \frac{G_\mu m_t^5}{16\sqrt{2}\pi^2 M_W^2} \int_0^1 \frac{dy \gamma_W}{(1 - y/\bar{y})^2 + \gamma_W^2} F_0(y)
\]

\[\gamma_W = \frac{\Gamma_W}{M_W}, \quad \bar{y} = \left(\frac{M_W}{m_t}\right)^2 \quad F_0(y) = 2(1 - y)^2(1 + 2y)\]

\[
\Gamma_t^{NLO} = \frac{G_\mu m_t^5}{16\sqrt{2}\pi^2 M_W^2} \int_0^1 \frac{dy \gamma_W}{(1 - y/\bar{y})^2 + \gamma_W^2} \left[ F_0(y) - \frac{2\alpha_s}{3\pi} F_1(y) \right]
\]

\[
F_1(y) = 2(1 - y)^2(1 + 2y) \left[ \pi^2 + 2\text{Li}_2(y) - 2\text{Li}_2(1 - y) \right]
+ 4y(1 - y - 2y^2) \ln(y) + 2(1 - y)^2(5 + 4y) \ln(1 - y)
- (1 - y)(5 + 9y - 6y^2).
\]

- In the limit $\gamma_W \rightarrow 0$

\[
\frac{\gamma_W}{(1 - y/\bar{y})^2 + \gamma_W^2} \rightarrow \pi \bar{y} \delta(y - \bar{y}).
\]

M. Jezabek, J. H. Kühn ’89
A. Denner, et al. ‘12
Jets:
★ Final-state quarks and gluons with pseudo-rapidity $|y| < 5$ converted into infrared-safe jets using $anti-k_T$ jet algorithm with $R=0.5$

Requirement:
★ exactly 2 b-jets, at least one light-jet, 2 charged leptons, and missing $p_T$

Final states:
★ have to fulfill the following kinematical requirements (fairly inclusive cuts)

\[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X \]

- $p_{T\ell} > 30 \text{ GeV}$,
- $p_{Tj} > 40 \text{ GeV}$,
- $p_{T\text{miss}} > 40 \text{ GeV}$,
- $\Delta R_{jj} > 0.5$,
- $\Delta R_{\ell\ell} > 0.4$,
- $|y_\ell| < 2.5$,
- $|y_j| < 2.5$,


**Scale Dependence**

- Total cross section @ LHC with 8 TeV (MSTW2008 PDF)

\[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X \]

\[
\begin{align*}
\sigma_{\text{HELAC-NLO}}^{\text{LO}} &= 183.1^{+112.2(61\%)}_{-64.2(35\%)} \text{ fb}, \\
\sigma_{\text{HELAC-NLO}}^{\text{NLO}} &= 159.7^{+33.1(21\%)}_{-7.9(5\%)} \text{ fb}.
\end{align*}
\]

- **NLO** corrections: -13%

- Theoretical uncertainties:
  - ★ 61% (48%) @ LO
  - ★ 21% (13%) @ NLO

\[ \mu_R = \mu_F = \mu_0 = m_t \]

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G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16
Hardest Light-Jet

- Upper panel: distributions and scale dependence bands: \( \{0.5m_t, m_t, 2m_t\} \)
- Lower panel: differential K-factor

- NLO do not rescale shape of LO
- Distortions up to 50\% with \( \mu_0 = m_t \)
- Properly described only via NLO
- Negative NLO in \( p_T \) tails
  \( \rightarrow \) LO higher than NLO

- The dynamic scale should depend on hardest jet \( p_T \)
- Asymptotic freedom \( \rightarrow \alpha_s \downarrow \) in tails
- Dependence on \( \alpha_s @ \text{LO} \gg @ \text{NLO} \)
- Would drive positive NLO/LO ratio in this region

\[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}j + X \]
Hardest Light-Jet

- Upper panel: distributions and scale dependence bands
- Lower panel: differential K-factor

- Negative, moderate but ... quite stable NLO corrections
- Dimensionless nature of $y_j$
- Receives contributions from various scales $\rightarrow$ also from these sensitive to threshold for $ttj$ production
- For $\mu_0 = m_t$ effects of phase-space regions close to $ttj$ threshold dominate

$$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

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Lepton and b-Jet

- Upper panel: distribution and scale dependence bands
- Lower panel: differential K-factor
- \( be^+ \) pair that returns the smallest invariant mass

\[
M_{be^+} = \sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}
\]

- If both top and W decay on-shell → end-point given by sharp cut
- Additional radiation & off-shell effects introduce smearing
- Highly sensitive to the details of the description of the process

\[
pp \rightarrow e^+ \nu e \mu^- \bar{\nu}_\mu b \bar{b} j + X
\]
Summary

- Complete description for $ttj$ process with “resonant” and “non-resonant” contributions at NLO QCD

- Further studies are needed:
  - Look for judicious choice of a dynamical scale
  - PDF uncertainties
  - Bottom-mass effects
  - Off-shell effects for differential distributions (comparison to NWA)

- Phenomenological applications $\rightarrow m_t$ extraction

- Shape-based $m_t$ measurement relies on precise modeling of differential distributions

- $m_t$ extraction $< 1$ GeV $\rightarrow$ Predictions should go beyond simple approximation of factorizing top production & decays
Outlook

- Alternative method for $m_t$
- $m_t$ from normalized differential cross section for $ttj$

\[ \mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \]

\[ \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}, \]

S. Alioli, et al. ‘13

- $\mathcal{R}$ has been calculated using $ttj @ NLO +$ POWHEG matched with PYTHIA
  → top-quark decays via PS with spin correlations @ LO

- Theoretical uncertainties & PDF uncertainties should affect $m_t$ extraction $< 1 \text{ GeV}$

- ATLAS @ 7 TeV: $m_t = 173.7 \pm 2.2 \text{ GeV}$

  ATLAS, arXiv:1507.01769

- Worth looking at
Backup slides...
ttj Process

- Background to supersymmetric particle production
- Top decays into W and b-quark $\rightarrow$ SM : $t \rightarrow Wb \approx 100$
- Decay channels: di-leptons ($Br = 4\%$), lepton+jet ($Br = 30\%$), all-jets ($Br = 46\%$)
  - **ttj signature**: jets, charged leptons & $p_T$ (miss) from invisible neutrinos
  - **Typical signals**: jets, charged leptons & $p_T$ (miss) due to escaping lightest supersymmetric particle (neutralino)

$\tilde{g} \rightarrow \geq 2 \text{ jet} + \text{MET} + \geq 0 \ell^\pm$

Chain decays of gluino

M. L. Mangano ‘09
ttj Process

- Top flavor violating resonances, singly produced in association with top @ LHC

- $\tilde{t} = t$ for $M = W', Z'_H$ and $\tilde{t} = t$ when $M = \phi^a$ (color triplet or sextet)

- $W'$ signal: $W' \rightarrow \bar{t}q$

- Production processes: $pp \rightarrow W't \rightarrow ttj$

$$m_{W'} \in \{200, \ldots, 600\} \text{ GeV}$$

$$\sigma_{7\text{ TeV}} \in \{40, \ldots, 4\} \text{ pb}$$

- ATLAS: $m_{W'} > 430 \text{ GeV} \quad \text{arXiv:1209.6593}$
b-Jet

- Upper panels: distributions and scale dependence bands
- Lower panels: differential $K$-factors

\[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}j + X \]

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16
Leptons

- Upper panels: distributions and the scale dependence bands
- Lower panels: differential $K$-factors

$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X$

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek ‘16
Theoretical Predictions for $ttj$

- NLO QCD corrections to on-shell $ttj$ production
  
  \textit{S. Dittmaier, P. Uwer, S. Weinzierl ‘07 ‘09}

- NLO QCD correction to on-shell $ttj$ production with LO decays
  
  \textit{K. Melnikov, M. Schulze ‘10}

- NLO QCD corrections to $ttj$ in NWA (with jet radiation in top-quark decays)
  
  \textit{K. Melnikov, M. Schulze ‘12}

- NLO QCD corrections to $ttj$ with full top-quark and W off-shell effects
  
  \textit{G. Bevilaqua, H. B. Hartanto, M. Kraus, M. Worek ‘16}

- NLO QCD correction to on-shell $ttj$ production + PS
  
  ★ \textbf{POWHEG} + \textbf{PYTHIA}, no spin correlations
  
  \textit{A. Kardos, C. G. Papadopoulosa, Z. Trocsanyi ‘11}

  ★ \textbf{POWHEG} + \textbf{PYTHIA/HERWIG} with spin-correlations @ LO
  
  \textit{S. Alioli, S. Moch, P. Uwer ‘12}

  ★ \textbf{MC@NLO} + \textbf{DEDUCTOR}, without top-quark decays
  
  \textit{M. Czakon, H. B. Hartanto, M. Kraus, M. Worek ‘15}
NWA for $ttj$

- Inclusive NLO $\sigma(ttj)$ in NWA convolution of production $\sigma(tt+nj)$ & $\Gamma(tt+nj)$ $n \leq 2$

$$d\sigma_{\text{incl}} = \Gamma_{t,\text{tot}}^{-2}(d\sigma_{tt+0j} + d\sigma_{tt+1j} + d\sigma_{tt+2j} + \cdots)$$

$$\otimes (d\Gamma_{tt+0j} + d\Gamma_{tt+1j} + d\Gamma_{tt+2j} + \cdots).$$

- Expanded version with terms up to $\alpha_s^4$ only

$$d\sigma^{\text{NLO}}_{tt+1j} = \Gamma_{t,\text{tot}}^{-2}(d\sigma_{tt+1j}^{\text{LO}}d\Gamma_{tt+1j}^{\text{LO}} + d\sigma_{tt}^{\text{LO}}d\Gamma_{tt+1j}^{\text{LO}} + (d\sigma_{tt+1j}^{\text{virt}} + d\sigma_{tt+2j}^{\text{real}})d\Gamma_{tt}^{\text{LO}} + d\sigma_{tt}^{\text{LO}}(d\Gamma_{tt+1j}^{\text{virt}} + d\Gamma_{tt+2j}^{\text{real}}))$$

$$+ d\sigma_{tt+1j}^{\text{real}}d\Gamma_{tt+1j}^{\text{real}} + d\sigma_{tt}^{\text{virt}}d\Gamma_{tt+1j}^{\text{LO}} + d\sigma_{tt}^{\text{LO}}d\Gamma_{tt}^{\text{virt}}).$$

K. Melnikov, M. Schulze '12
NWA for $ttj$

$LHC @ 7$ TeV with inclusive cuts

\[ \sigma_{LO} = 316.9\text{(Pr)} + 33.4\text{(Dec)} = 350.3\text{ fb}, \]
\[ \sigma_{NLO} = 323\text{(Pr)} + 40.5\text{(Dec)} - 75.5\text{(Mix)} = 288\text{ fb}. \]

14%  
26%

K. Melnikov, M. Schulze '12

Full NWA versus NWA with LO decays