$t\bar{t} + \gamma$ Production
and the
Top Quark Electric Charge

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in collaboration with K. Melnikov and A. Scharf

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One of Tevatron`s greatest legacy:

- Discovery of the top quark
- Measurement of the cross section
- Determination of the mass
- Measurement of the FB asymmetry
- Plus: decay width, spin correlations, W helicity fractions, $|V_{tb}|^2$, ...
What do we know about top quark electroweak couplings?

- electric charge,
- magn./electr. dipole mom.,
- weak charge,
- Yukawa coupl.
Electroweak couplings

What do we know about top quark electroweak couplings?

- electric charge,
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- weak charge,
- weak charge,
- Yukawa coupl.

This is where the LHC takes over:

\[ pp \rightarrow t\bar{t} + \gamma \]
\[ pp \rightarrow t\bar{t} + Z \]
\[ pp \rightarrow t\bar{t} + \text{Higgs} \]

Studies of \( t\bar{t}Z \) and \( t\bar{t}H \) require at least \( \mathcal{L} = 100 \text{ fb}^{-1} \) (14 TeV)

Let's study \( t\bar{t}\gamma \) first and see what we can do for \( Q_t \).
Top quark electric charge

What do we know about the top quark electric charge?
Top quark electric charge

What do we know about the top quark electric charge?

[Chang,Chang,Ma]: $m_{Q_{4u}} = 172$ GeV, $m_{t_{2/3}} \geq 356$ GeV

$Q_t = 2/3$

$Q_t = -4/3$

✓ electroweak precision tests, ✓ Tevatron searches, ✓ LHC searches
Top quark electric charge

CDF: 5.6 fb\(^{-1}\) (2011)

1) identify W-boson charge through lepton charge
2) pair b-jet with W-boson (kinem. fits to \(m_{\text{top}}\), \(M_W\))
3) measure b-jet charge (JetCharge Algorithm)

\[
\text{SM top quark charge } \leftrightarrow \ Q(W) \cdot Q(\text{b-jet}) < 0
\]

\[
\text{XM top quark charge } \leftrightarrow \ Q(W) \cdot Q(\text{b-jet}) > 0
\]

result: 416 SM events vs. 358 XM events
⇒ Exclusion of pure XM hypothesis with 95% C.L.

only 56\% signal purity for SM top quarks
$t\bar{t}$ pairs in association with a photon

\[ pp \rightarrow t\bar{t} + \gamma \text{ at the LHC} \]
**$t\bar{t}$ pairs in association with a photon**

\[ pp \rightarrow t\bar{t} + \gamma \text{ at the LHC} \]

We are interested in the correlation $\sigma_{t\bar{t}\gamma}(Q_{top}^2)$.

Charge measurement is mainly a counting experiment.

NLO normalization is important!

**LHC:** high energy+luminosity \quad \Rightarrow \quad \text{expect } \sim 1000 \text{ events from } 10 \text{ fb}^{-1}

dominance of gluon flux \quad \Rightarrow \quad \text{few photons from ISR (} \sim Q_{top} \text{)}

**but:** „pollution“ from photon emission off top decay products (FSR)
$t\bar{t}$ pairs in association with a photon

[Baur, Juste, Rainwater, Orr]:

**Leading-order study**

At the LHC with 10 fb$^{-1}$ an accuracy of 10% on $Q_t$ is feasible. „If scale uncertainty is reduced to 10%, an improvement in precision by a factor of two seems possible“

[Duan, Ma, Zhang, Han, Guo, Wang]:

**Next-to-leading-order QCD calculation**

- small/large K-factor at the Tevatron/LHC
- FB asymmetry of -11%
- stable top quarks
Our calculation

Hadronic production of $t\bar{t} + \gamma$ at NLO QCD including decays.

\[ pp \rightarrow t\bar{t} + \gamma \rightarrow b\bar{b} \ell \nu jj + \gamma \]

2 → 7 process is complicated at NLO QCD.

What is important?

- spin correlations: acceptances
- photon radiation in decay: large contribution
- NLO corrections in production & decay: normalization, scale dependence, leading soft/collinear emissions

What can be approximated?

- largely off-shell top quarks, W’s: neglect non-resonant contributions
  ⇒ narrow width approximation valid up to $O(\alpha_s \Gamma/m)$
- neglect shower effects and higher order threshold corrections: observables under consideration should not be very sensitive
Results

**LHC**

leptons+jets channel

std. acceptance cuts

\[ \sigma_{t\bar{t}\gamma}^{\text{LO}} = 74.5^{+24.0}_{-16.9} \text{ fb} \]

\[ \sigma_{t\bar{t}\gamma}^{\text{NLO}} = 138^{+30}_{-23} \text{ fb} \]

- large K-factor ~1.9
- no reduction of scale dependence  (opening up of q-g channel at NLO)
Important:
A large fraction of events from radiative top decays

\[ \frac{\sigma_{\text{decay}}}{\sigma_{\text{tot}}} = 56\% \]

FSR photons are not very soft and well separated from b quarks.
Results

**Exotic top quarks**

\[
\sigma_{tt\gamma}^{\text{NLO}} = 138 \text{ fb} \quad Q_t = \frac{2}{3} \rightarrow -\frac{4}{3} \quad \sigma_{tt\gamma}^{\text{NLO}} = 243 \text{ fb}
\]

Naive expectation of $Q_t^2$ scaling fails because of large contribution from radiative top decay
Results

Three strategies:

1.) measure the total cross section

2.) study ratio of cross sections

3.) apply cuts to enhance $Q_t^2$ dependence
2.) Ratio of cross sections $\frac{\sigma_{t\bar{t}\gamma}}{\sigma_{tt}}$

\[
\begin{align*}
\sigma_{t\bar{t}\gamma}^{Q_t=2/3} / \sigma_{tt} &= \left\{ \begin{array}{ll} 5.66^{+0.03}_{-0.02} \times 10^{-3}, & \text{LO;} \\ 6.33^{+0.26}_{-0.14} \times 10^{-3}, & \text{NLO,} \end{array} \right. \\
\sigma_{t\bar{t}\gamma}^{Q_t=-4/3} / \sigma_{tt} &= \left\{ \begin{array}{ll} 10.4^{+0.2}_{-0.2} \times 10^{-3}, & \text{LO;} \\ 11.2^{+0.3}_{-0.2} \times 10^{-3}, & \text{NLO.} \end{array} \right.
\end{align*}
\]

- Ratios are significantly more stable against NLO corrections
- Small scale uncertainties
- Some experimental uncertainties cancel
3.) Choose cuts to enhance $Q_t^2$ dependence

Inspired by U.Baur et.al.: suppress radiative top decays

\[ m_T(b\ell\gamma; E_T^{\text{miss}}) > 180 \text{ GeV}, \quad m_T(\ell\gamma; E_T^{\text{miss}}) > 90 \text{ GeV}, \]
\[ 160 \text{ GeV} < m(bjj) < 180 \text{ GeV}, \quad 70 \text{ GeV} < m(jj) < 90 \text{ GeV} \]
3.) Choose cuts to enhance $Q_t^2$ dependence

- strong reduction of scale dependence
- smaller K-factor
- enhanced $Q_t$ dependence
3.) Choose cuts to enhance $Q_t^2$ dependence

- strong reduction of scale dependence
  smaller K-factor

- enhanced $Q_t$ dependence

**However:**
- much smaller cross section
  $\sigma^{\text{nocuts}}_{\text{SM } t\bar{t}\gamma} = 138 \text{ fb}$
  $\sigma^{\text{cuts}}_{\text{SM } t\bar{t}\gamma} = 26 \text{ fb}$
3.) Choose cuts to enhance $Q_t^2$ dependence

Luminosity $\mathcal{L}$ to separate SM and XM hypothesis at 3\(\sigma\) C.L.:

$$\frac{\mathcal{L}_{\text{no cuts}}}{\mathcal{L}_{\text{cuts}}} = \begin{cases} 1.98 \pm 0.02, & \text{LO;} \\ 1.12 \pm 0.08, & \text{NLO;} \end{cases}$$

100\% gain at LO is reduced to 10\% gain at NLO
SUMMARY

- $t\bar{t} + \gamma$ is an interesting LHC signal that can be studied soon

- we provide NLO QCD predictions for realistic observables

- large fraction of events from radiative top decays

- measurement of the top quark electric charge at the LHC is the first step towards studies of other electroweak couplings
SUMMARY

- $t\bar{t} + \gamma$ is an interesting LHC signal that can be studied soon
- we provide NLO QCD predictions for realistic observables
- large fraction of events from radiative top decays
- measurement of the top quark electric charge at the LHC is the first step towards studies of other electroweak couplings
- what I left out:
  - we use unitarity methods to calculate virtual corrections
  - $t\bar{t} + \gamma$ measurement at the Tevatron (New Physics search)
  - FB asymmetry
Extras
Impact of NLO corrections in the decay

LHC (7TeV) semi-lept. channel std. accept. cuts
-13% to total cross section
Markus Schulze, Johns Hopkins University

**Tevatron results**

\[ \sigma_{t\bar{t}\gamma}^{\text{LO}} = 2.85^{+1.14}_{-0.75} \text{ fb} \]

\[ \sigma_{t\bar{t}\gamma}^{\text{NLO}} = 2.64^{+0.21}_{-0.03} \text{ fb} \]

\[ \frac{d\sigma}{dp_T(\gamma)} / \frac{d\sigma}{dp_T(\gamma)} \]

\[ \text{K-factor} \]

\[ d\sigma_{t\bar{t}\gamma} / dp_T(\gamma) \]

\[ 14 \pm 1 \text{ events vs. CDF: } 14 \pm 3 \text{ events} \]

(LO: 16\pm5 events)
Extras

Tevatron results

<table>
<thead>
<tr>
<th>Standard Model Source</th>
<th>$e\gamma b E_T$</th>
<th>$\mu\gamma b E_T$</th>
<th>$(e + \mu)\gamma b E_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}\gamma$ (semileptonic)</td>
<td>$5.98 \pm 1.10$</td>
<td>$5.21 \pm 0.97$</td>
<td>$11.19 \pm 2.04$</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$ (dileptonic)</td>
<td>$1.47 \pm 0.27$</td>
<td>$1.27 \pm 0.24$</td>
<td>$2.74 \pm 0.50$</td>
</tr>
<tr>
<td>$W^{\pm}\gamma$</td>
<td>$0 \pm 0.07$</td>
<td>$0 \pm 0.07$</td>
<td>$0 \pm 0.09$</td>
</tr>
<tr>
<td>$W^{\pm}\gamma$</td>
<td>$0 \pm 0.05$</td>
<td>$0.05 \pm 0.05$</td>
<td>$0.05 \pm 0.07$</td>
</tr>
<tr>
<td>$W^{\pm}\gamma$</td>
<td>$0.15 \pm 0.07$</td>
<td>$0.06 \pm 0.05$</td>
<td>$0.21 \pm 0.08$</td>
</tr>
<tr>
<td>$W^Z$</td>
<td>$0.05 \pm 0.05$</td>
<td>$0.05 \pm 0.05$</td>
<td>$0.09 \pm 0.06$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$0.06 \pm 0.03$</td>
<td>$0.06 \pm 0.03$</td>
<td>$0.11 \pm 0.03$</td>
</tr>
<tr>
<td>Single Top (s-channel)</td>
<td>$0.09 \pm 0.10$</td>
<td>$0 \pm 0.10$</td>
<td>$0.09 \pm 0.13$</td>
</tr>
<tr>
<td>Single Top (t-channel)</td>
<td>$0.14 \pm 0.14$</td>
<td>$0.13 \pm 0.14$</td>
<td>$0.27 \pm 0.19$</td>
</tr>
<tr>
<td>$\tau \rightarrow \gamma$ fake</td>
<td>$0.20 \pm 0.08$</td>
<td>$0.10 \pm 0.05$</td>
<td>$0.29 \pm 0.09$</td>
</tr>
<tr>
<td>Jet faking $\gamma$ ($e\gamma E_T, j \rightarrow \gamma$)</td>
<td>$5.75 \pm 1.76$</td>
<td>$1.79 \pm 1.56$</td>
<td>$7.54 \pm 2.53$</td>
</tr>
<tr>
<td>QCD Jets</td>
<td>$1.47 \pm 0.37$</td>
<td>$1.02 \pm 0.32$</td>
<td>$2.50 \pm 0.51$</td>
</tr>
<tr>
<td>$ee \gamma b, e \rightarrow \gamma$</td>
<td>$0.38 \pm 0.38$</td>
<td>$0.02 \pm 0.020$</td>
<td>$0.40 \pm 0.38$</td>
</tr>
<tr>
<td>$\mu e \gamma b, e \rightarrow \gamma$</td>
<td>$0.94 \pm 0.19$</td>
<td>$-0.49 \pm 0.11$</td>
<td>$0.49 \pm 0.11$</td>
</tr>
<tr>
<td>Total SM Prediction</td>
<td>$16.7 \pm 2.2$ (tot)</td>
<td>$10.3 \pm 1.9$ (tot)</td>
<td>$26.9 \pm 3.4$ (tot)</td>
</tr>
<tr>
<td>Observed in Data</td>
<td>17</td>
<td>13</td>
<td>30</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary 6.0 fb$^{-1}$

- Data$(e+\mu)$
- $t\bar{t}\gamma$
- $W\gamma + HF$
- fake b-tag
- fake $j$ fakes $\gamma$
- fake $l/E_T$
- EWK
- $\tau$ fake $\gamma$
- $e$ fake $\gamma$

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Coupling the photon at NLO

Master formula: \[ d\sigma^{\text{NWA}} = d\sigma_{t\bar{t}\gamma} dB_t dB_{\bar{t}} + d\sigma_{t\bar{t}} (dB_{t\gamma} dB_{\bar{t}} + dB_t dB_{\bar{t}\gamma}) \]

expand in \( \alpha_s \):

\[ d\sigma^{\delta\text{NLO}} = d\sigma_{t\bar{t}\gamma}^{\delta\text{NLO}} dB_t^\text{LO} dB_{\bar{t}}^\text{LO} \]

\[ + d\sigma_{t\bar{t} \gamma}^\text{LO} \left( dB_t^{\delta\text{NLO}} dB_{\bar{t}}^\text{LO} + dB_t^\text{LO} dB_{\bar{t}}^{\delta\text{NLO}} \right) \]

\[ + d\sigma_{t\bar{t}}^{\delta\text{NLO}} \left( dB_{t\gamma}^\text{LO} dB_{\bar{t}}^\text{LO} + dB_{t\gamma}^\text{LO} dB_{\bar{t}\gamma}^\text{LO} \right) \]

\[ + d\sigma_{t\bar{t}}^\text{LO} \left( dB_{t\gamma}^{\delta\text{NLO}} dB_{\bar{t}}^\text{LO} + dB_{t\gamma}^\text{LO} dB_{\bar{t}}^{\delta\text{NLO}} \right) \]

\[ + dB_{t\gamma}^\text{LO} dB_{\bar{t}}^{\delta\text{NLO}} + dB_{t\gamma}^{\delta\text{NLO}} dB_{\bar{t}}^\text{LO} \]
**FB asymmetry in ttbar+photon**

\[ A_{FB} = \frac{N(y_t>0) - N(y_t<0)}{N(y_t>0) + N(y_t<0)} \]

- \( t\bar{t} \) asymmetry appears only at NLO QCD \[ [Kühn,Rodrigo] \]
  Theory prediction \( A_{FB}(t\bar{t}) = 5\% \) in tension with measurement \( (2\sigma) \)
  Complete NNLO correction unknown, but indications for robustness

- \( t\bar{t} + \gamma \) asymmetry appears already at LO
  \[ A_{FB}^{LO}(t\bar{t}\gamma) = -17\%, \quad A_{FB}^{NLO}(t\bar{t}\gamma) = -12\% \]
  The 5\% reduction at NLO can be understood. \[ [Melnikov,MS : t\bar{t} + \text{jet}] \]
  Similar effect for \( t\bar{t}\text{jet} \)
  \[ A_{FB}^{LO}(t\bar{t}\text{jet}) = -8\%, \quad A_{FB}^{NLO}(t\bar{t}\text{jet}) = -2\% \]
FB asymmetry in ttbar+photon
Extraction of total cross section

Measure $\sigma_{b\bar{b}l\nu jj\gamma}^{\text{meas.}}$ and extract $\sigma_{t\bar{t}\gamma}$ through dividing by branchings

$$\sigma_{t\bar{t}\gamma} = \sigma_{b\bar{b}l\nu jj\gamma}^{\text{meas.}} \times B(t \rightarrow b\ell\nu)^{-1} \times B(t \rightarrow \bar{b}jj)^{-1}$$

is wrong.

Instead, the radiative top decays have to be treated as „background“, 

$$\sigma_{t\bar{t}\gamma} = \left(\sigma_{b\bar{b}l\nu jj\gamma}^{\text{meas.}} - \sigma_{b\bar{b}l\nu jj\gamma}^{\text{decay}}\right) \times B(t \rightarrow b\ell\nu)^{-1} \times B(t \rightarrow \bar{b}jj)^{-1}.$$