$t\bar{t} + \gamma$ production at NLO QCD and the top quark electric charge

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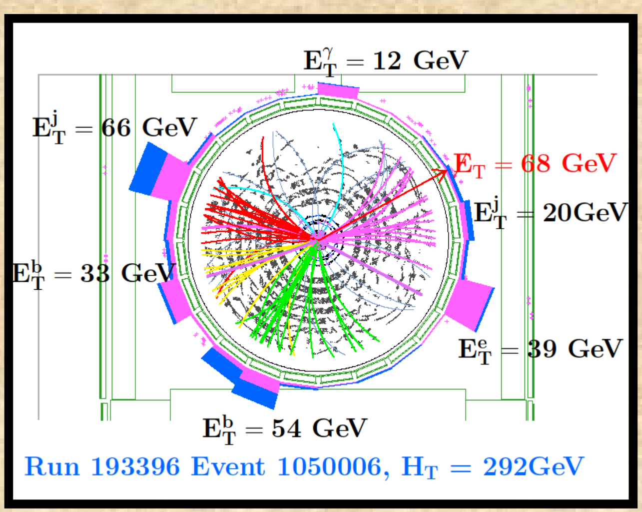
$t\bar{t}\gamma$ production

- Cross-section (one identified lepton+jets channel)

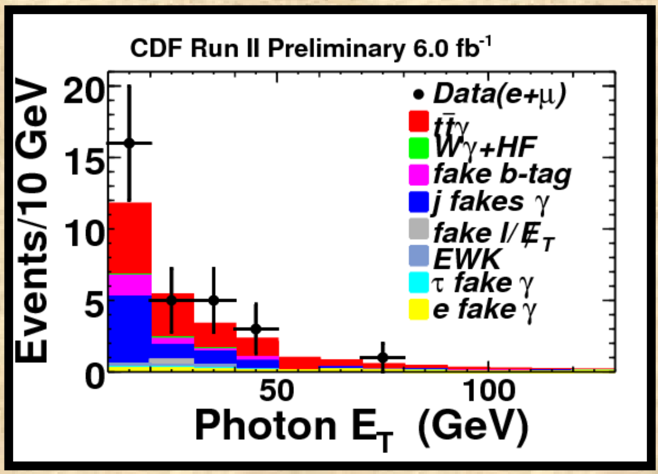
$$\sigma_{t\bar{t}\gamma}(7\ \text{TeV}) \propto \mathcal{O}(10)\ \text{fb}$$

→ **$t\bar{t}\gamma$ can be studied with 5 fb^{-1}**



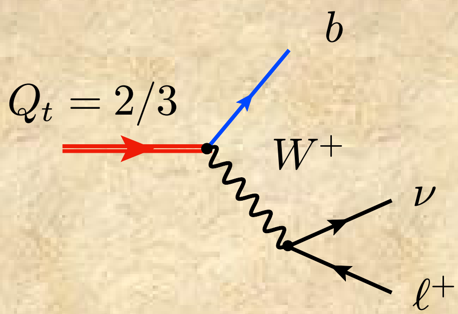
- Determine top-quark electromagnetic properties
  - Top-quark electric charge Q_t

- Possible background for New Physics signals
  - CDF (2011): $l\gamma E_{\mathrm{T,miss}} + b-$jet production

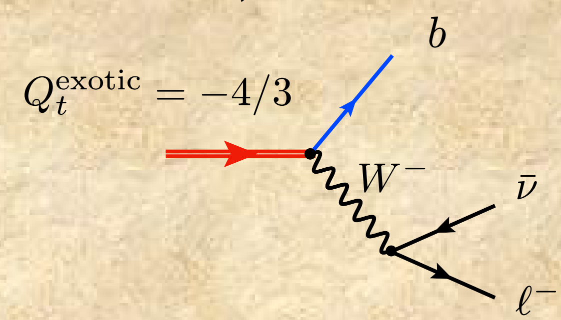


The top-quark electric charge

- $t\bar{t}$ production
  - Exotic quark: $m_t^{\text{measured}} = m_t^{\text{exotic}}, \quad Q_t^{\text{exotic}} = -4/3$ **Chang, Chang, Ma (1998)**
    - In agreement with electroweak precision data
    - In agreement with direct searches (Tevatron & LHC)



Standard Model

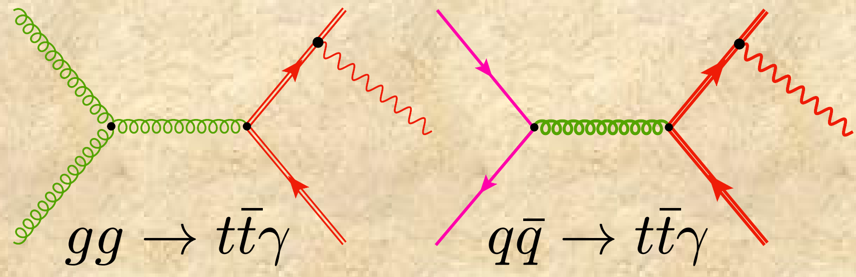


Exotic quark fakes SM anti-top

  - DZero (2007), 370 pb^{-1}: Percentage of exotic top-events < 80 % at 90. C.L.
  - CDF (2011) 5.6 fb^{-1}: $Q_t = -4/3$ **is excluded at 95 % C.L.**

The top-quark electric charge

- How well can we measure Q_t in $t\bar{t}\gamma$ production ?
  - Leading order study including top and W decays — Baur, Buice, Juste, Orr, Rainwater (2005, 2007)
  - $\frac{\Delta Q_t}{Q_t} \propto 0.1$ seems possible with 10 fb^{-1} at the LHC
  - At the Tevatron limited sensitivity to Q_t
  - Theoretical scale uncertainty is one limiting factor



$t\bar{t}\gamma$ composition (LO): $p_T^\gamma > 20$ GeV

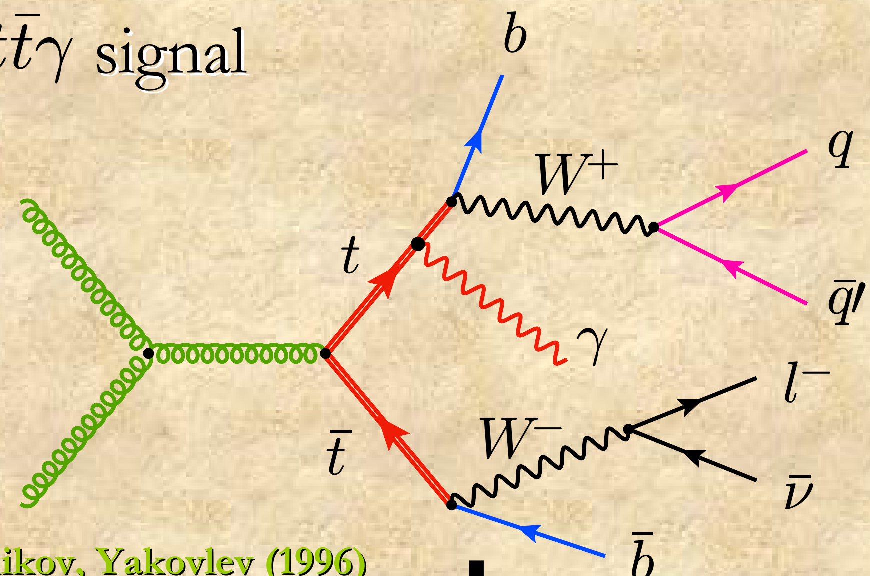
Tevatron:	1 %	99 %
LHC:	66 %	34 %

- NLO QCD calculation for stable top quarks — Duan, Ma, Zhang, Han, Guo, Wang (2009)
  - Large K-factor at the LHC
  - Small K-factor at the Tevatron

$t\bar{t}\gamma$ production

- We want a realistic description of the $t\bar{t}\gamma$ signal

  Full NLO calculation is very complicated



- Apply narrow width approximation
  - On-shell condition for top's and W's
  - Neglect off-shell and non-resonant effects

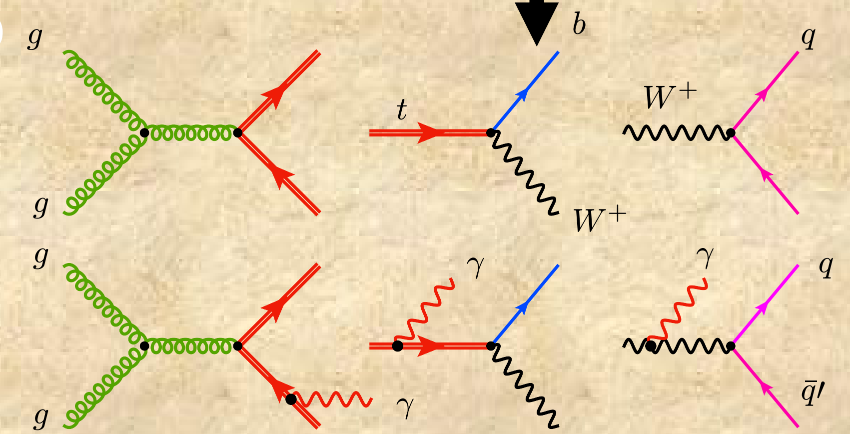
Melnikov, Yakovlev (1996)
Beenakker, Berends, Chapovsky (1999)
Denner, Dittmaier, Kallweit, Pozzorini (2010)
Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek (2010)

- Two kinds of contributions at NLO
  - γ radiation in production

    $$pp \to t\bar{t} + \gamma \to b\bar{b}jj\ell^+\nu + \gamma$$

  - γ radiation in decay

    $$pp \to t\bar{t} \to b\bar{b}jj\ell^+\nu + \gamma$$



NLO corrections

- $pp \to t\bar{t}$ — Melnikov, Schulze (2009)
- $pp \to t\bar{t}\gamma$

Virtual Corrections

- D-dimensional unitarity — Ellis, Giele, Kunszt (2007); Giele, Kunszt, Melnikov (2008)
- Cross-check: Feynman-diagrams with OPP — Ossola, Papadopoulos, Pittau (2006)

Real Corrections

- Dipoles with α-dependence — Catani, Seymour (1996); Nagy (2001); Catani, Dittmaier, Seymour, Trocsanyi (2002); Bevilacqua,Czakon,Papadopoulos,Pittau,Worek(2009)

- $t \to bW^+, \bar{t} \to \bar{b}W^-$
- $t \to bW^+\gamma, \bar{t} \to \bar{b}W^-\gamma$

Feynman-diagrams + PV, Feynman-diagrams + OPP, Dipoles with α-dependence

- No NLO corrections to hadronic W decays but we allow photon radiation

$t\bar{t}\gamma$ @ NLO

Leading order

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}\gamma}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\left(\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\gamma}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}\gamma}\right)$$

Comparison with Duan, Ma, Zhang, Han, Guo, Wang for stable top-quarks

Next-to-leading order

$$\begin{aligned}
\mathrm{d}\sigma^{\delta\mathrm{NLO}} &= \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}\gamma}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} \\
&+ \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}\gamma}\left(\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\right) \\
&+ \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}}\left(\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\gamma}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}\gamma}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\right) \\
&+ \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\Big(\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\gamma}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}\gamma}\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t} \\
&\qquad + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\gamma}\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}\gamma}\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t}\Big)
\end{aligned}$$

Results

Acceptance cuts (Tevatron, lepton+jets):

$p_T^\gamma > 10$ GeV $R(\gamma, \ell) > 0.4$

$p_T^\ell > 20$ GeV $R(\gamma, j) > 0.4$

$p_T^j > 15$ GeV $R(\gamma, j_b) > 0.4$

$p_T^{j_b} > 15$ GeV $|y_\ell| < 1.1$

$E_T^{miss} > 20$ GeV $|y_j| < 2$

$|y_{j_b}| < 2$

$|y_\gamma| < 1.1$

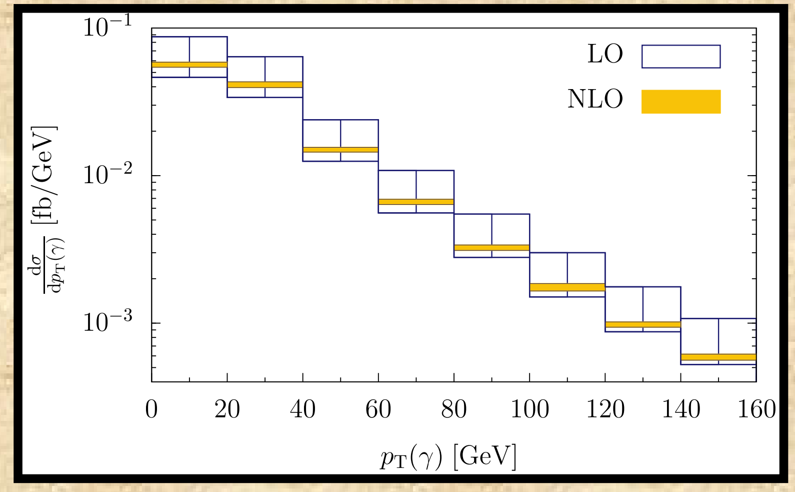
$$H_T = E_T^{miss} + \sum_i E_T^i > 200 \text{ GeV}$$

kT jet algorithm: $\Delta R(j,j) > 0.4$

Photon isolation condition Frixione (1998)

Tevatron:

- NLO: $\sigma_{t\bar{t}\gamma} = 2.64$ fb
- K-factor: K = 0.93
- Reduction of scale dependence



$m_t/2 < \mu < 2m_t$

$$\sigma_{t\bar{t}\gamma} = 2.64 \text{ fb} = 1.15 \text{ fb} + 1.49 \text{ fb}$$

Photon radiation in production

Photon radiation in decay (56 %)

Results

Acceptance cuts (LHC , lepton+jets):

$p_T^\gamma > 20$ GeV $\quad R(\gamma,\ell) > 0.4$

$p_T^\ell > 20$ GeV $\quad R(\gamma,j) > 0.4$

$p_T^j > 20$ GeV $\quad R(\gamma,j_b) > 0.4$

$p_T^{j_b} > 20$ GeV $\quad |y_\ell| < 2.5$

$E_T^{\mathrm{miss}} > 20$ GeV $\quad |y_j| < 2.5$

$|y_{j_b}| < 2$

$|y_\gamma| < 2.5$

$$H_T = E_T^{\mathrm{miss}} + \sum_i E_T^i > 200 \text{ GeV}$$

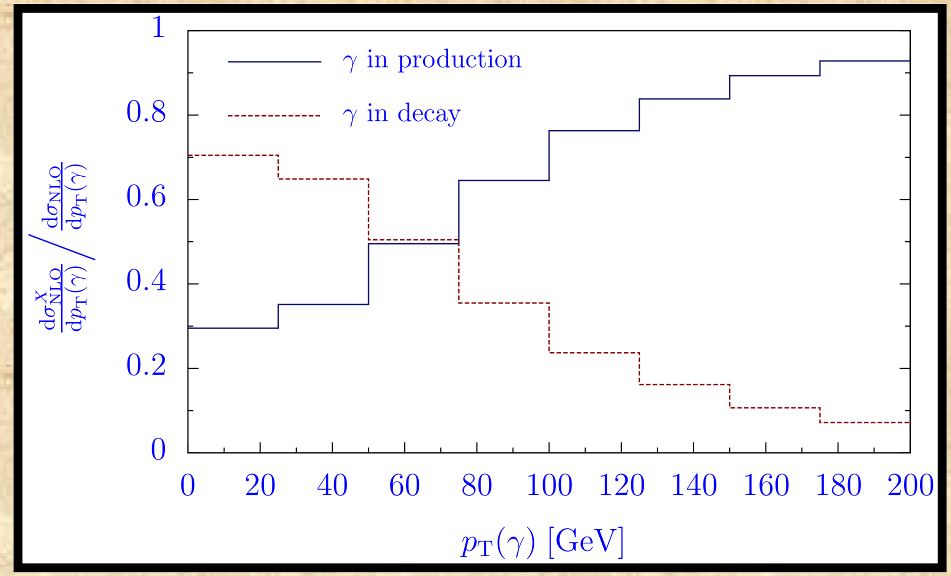
kT jet algorithm: $\Delta R(j,j) > 0.4$

Photon isolation condition Frixione (1998)

LHC: $\sigma_{t\bar{t}\gamma} = 138 \text{ fb} = 60.9 \text{ fb} + 77.1 \text{ fb}$

Photon radiation in production

Photon radiation in decay (56 %)

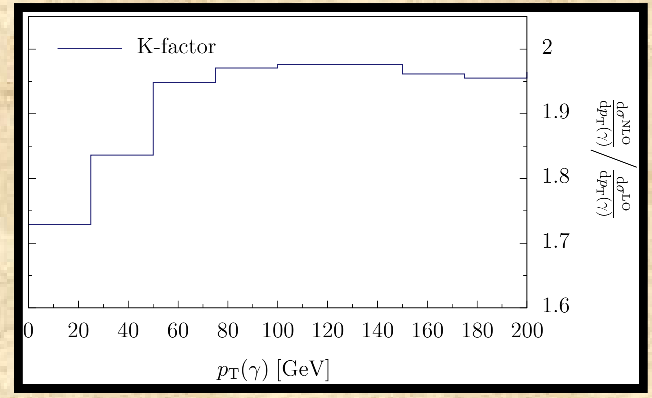


Photon radiation in decay is essential

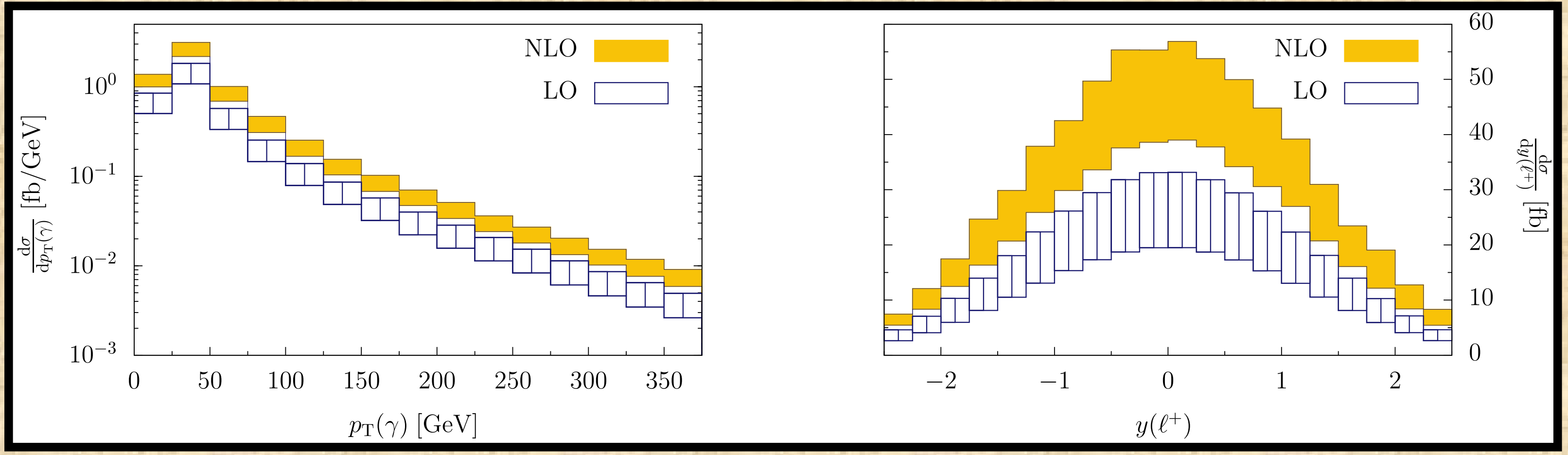
Results

LHC (14 TeV):

- **LO:** $\sigma_{t\bar{t}\gamma} = 74.5 \text{ fb}$
- **NLO:** $\sigma_{t\bar{t}\gamma} = 138 \text{ fb}$
- **K-factor: K = 1.85**



- **No reduction of scale dependence: New partonic channel at NLO** $(qg \to t\bar{t}\gamma q)$



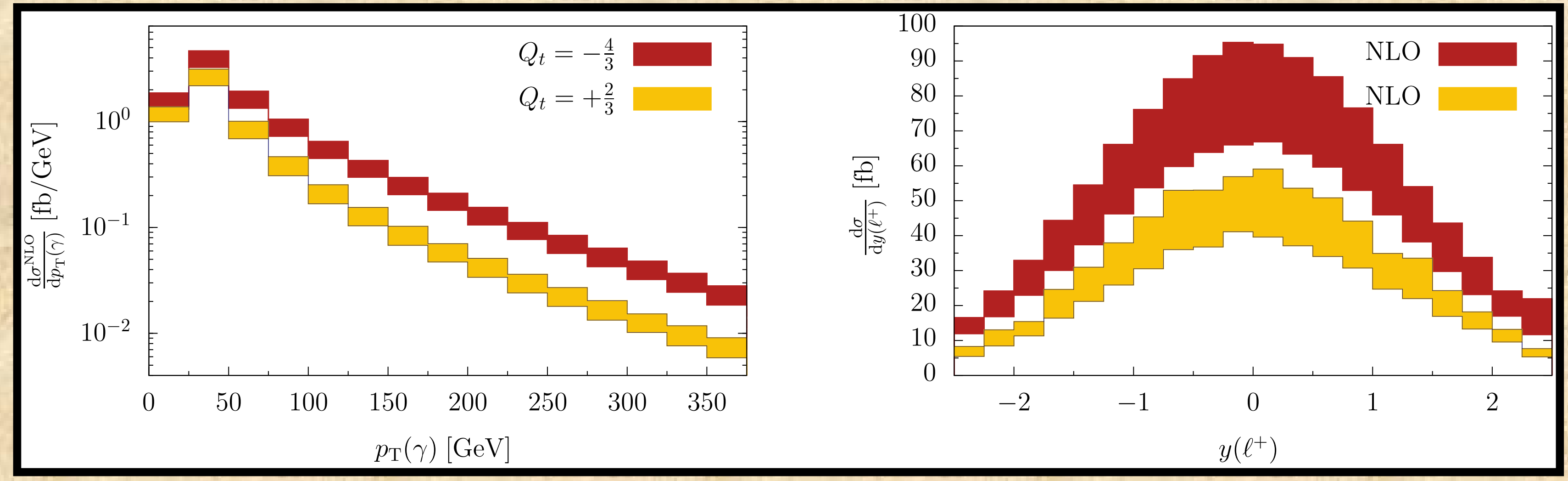
$m_t/2 < \mu < 2m_t$

- **LHC (7 TeV) @ NLO:** $\sigma_{t\bar{t}\gamma} = 26 \text{ fb}$

Q_t determination

- Exotic quark @ NLO

$$\sigma_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t \to Q_t^{\text{exotic}} = -4/3} \sigma_{t\bar{t}\gamma} = 243 \text{ fb}$$

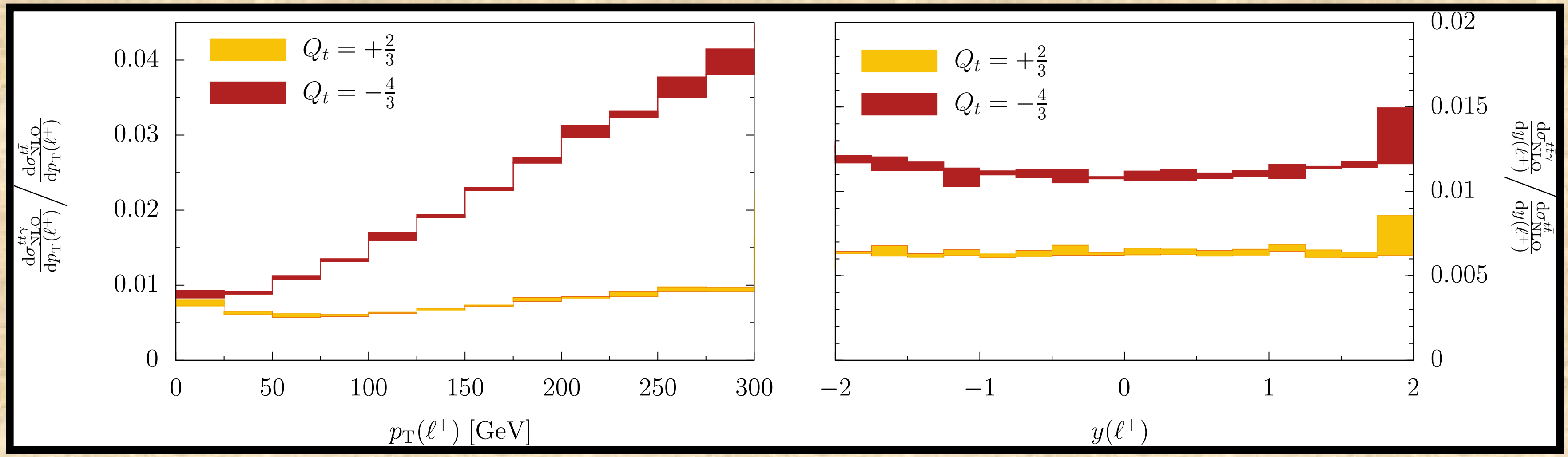


- Q_t^{exotic} can be clearly distinguished from Q_t

Naïve expectation, $\sigma_{t\bar{t}\gamma} \propto Q_t^2$ **fails** $\quad R = \frac{\sigma_{t\bar{t}\gamma}(Q_t^{\text{exotic}})}{\sigma_{t\bar{t}\gamma}(Q_t)} = 1.76$

Q_t determination

Consider ratio of $t\bar{t}\gamma/t\bar{t}$



$$\frac{\sigma^{Q_t}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = \begin{cases} 5.66^{+0.03}_{-0.02} \times 10^{-3}, & \text{LO;} \\ 6.33^{+0.26}_{-0.14} \times 10^{-3}, & \text{NLO,} \end{cases} \qquad \frac{\sigma^{Q_t^{\rm exotic}}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = \begin{cases} 10.4^{+0.2}_{-0.2} \times 10^{-3}, & \text{LO;} \\ 11.2^{+0.3}_{-0.2} \times 10^{-3}, & \text{NLO.} \end{cases}$$

- ❑ **Ratio is very stable against NLO corrections (~ 10 %)**
- ❑ **Small scale dependence**
- ❑ **Cancellation of experimental systematic uncertainties**

Q_t determination

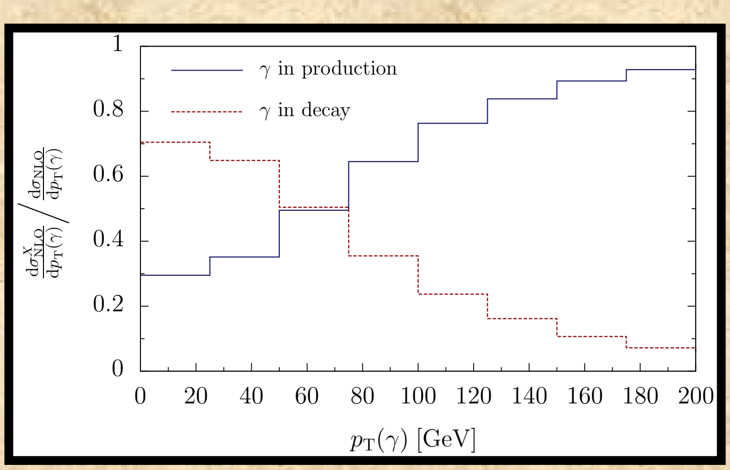
How to increase the Q_t dependence ?

→ **Apply cuts to suppress photon emission from decay**

Inspired by Baur, Buice, Orr (2005)

$$m_{\mathrm{T}}(j_b\ell\gamma, E_{\mathrm{T}}^{\mathrm{miss}}) > 180 \text{ GeV}, \quad m_{\mathrm{T}}(\ell\gamma, E_{\mathrm{T}}^{\mathrm{miss}}) > 90 \text{ GeV},$$

$$160 \text{ GeV} < m(j_b, j, j) < 180 \text{ GeV}, \quad 70 \text{ GeV} < m(j, j) < 90 \text{ GeV}.$$



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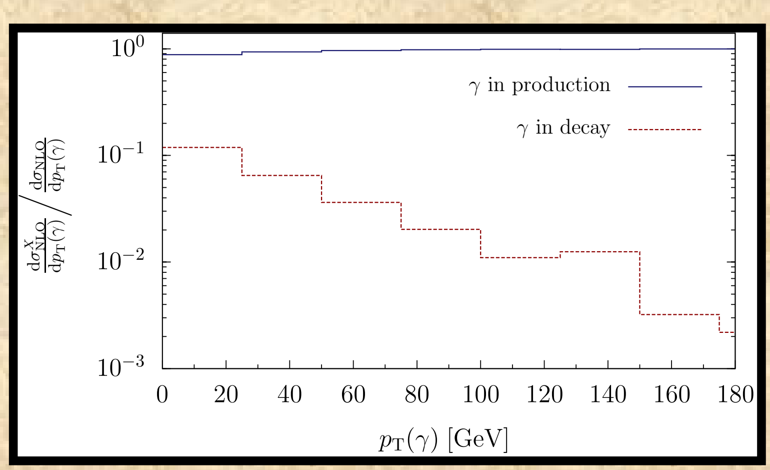
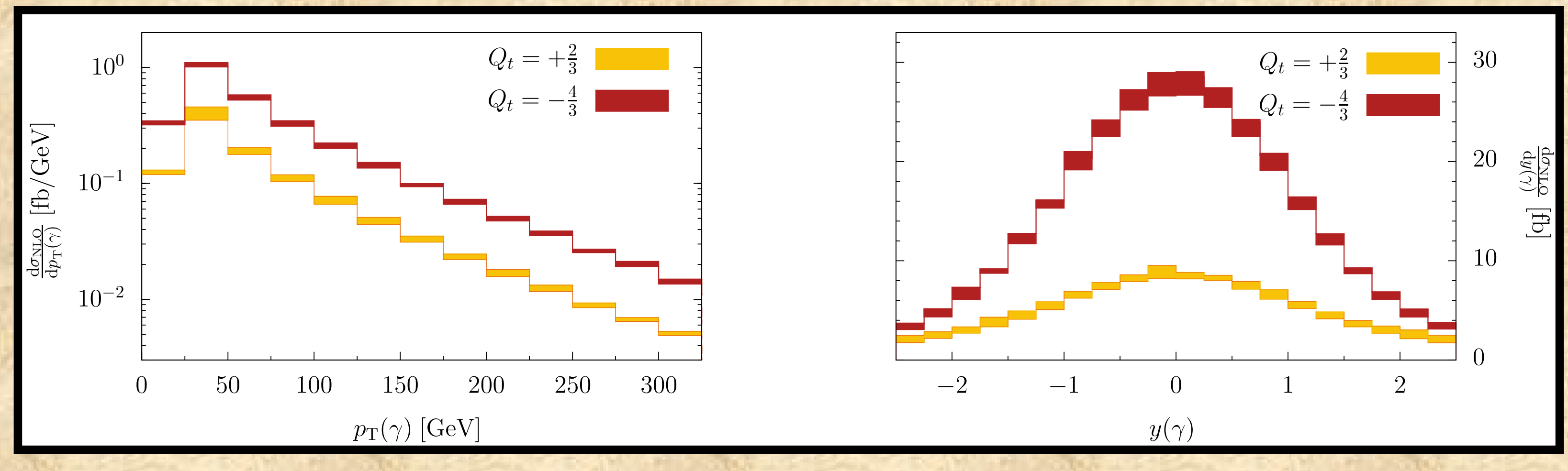


Q_t determination

With suppression cuts: $R = \frac{\sigma_{t\bar{t}\gamma}(Q_t^{\text{exotic}})}{\sigma_{t\bar{t}\gamma}(Q_t)} = 2.88$



Pros:

- **Improved scaling with Q_t**
- **Smaller K-factor (K =1.14)**
- **Reduced scale uncertainty**

Cons:

- **Significant reduction of signal**

$\sigma_{t\bar{t}\gamma}^{\text{tot}}(Q_t) = 27 \text{ fb}, \quad \sigma_{t\bar{t}\gamma}^{\text{tot}}(Q_t^{\text{exotic}}) = 77 \text{ fb}$

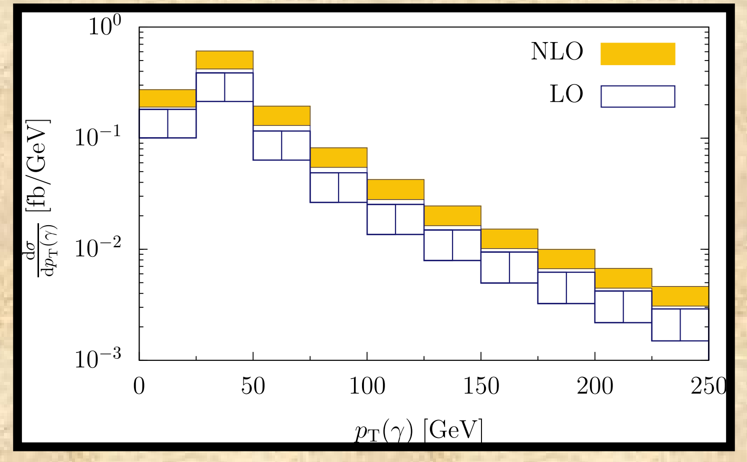
~80 % of the signal is lost

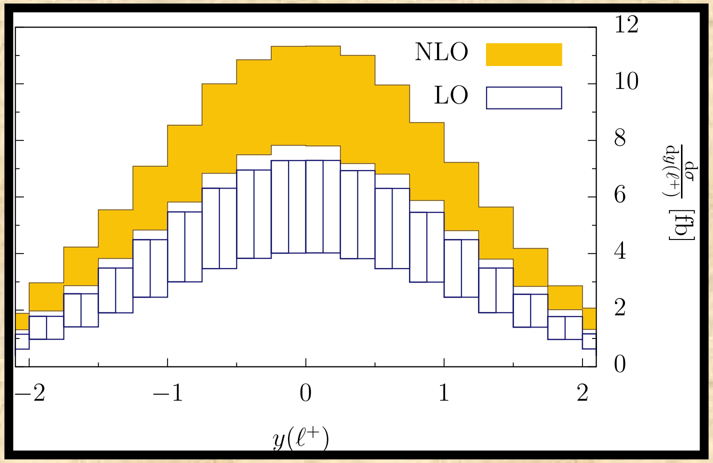
Summary & Outlook

- We calculated the NLO QCD corrections to $t\bar{t}\gamma$ production
- Flexible setup:
  - Production and decays of top-quarks at NLO
  - Photon radiation off all charged particles
- Large contributions from photon emission off decay products
- $t\bar{t}\gamma$ is ideal to determine the top-quark electric charge
  - Ratio of $t\bar{t}\gamma/t\bar{t}$ is very stable against NLO corrections

Results (LHC at 7 TeV)

Same acceptance cuts as for 14 TeV





Results (Tevatron)

$p_T^\ell > 20$ GeV $\quad |y^\ell| < 1.1$

$p_T^\gamma > 10$ GeV $\quad |y^\gamma| < 1.1$

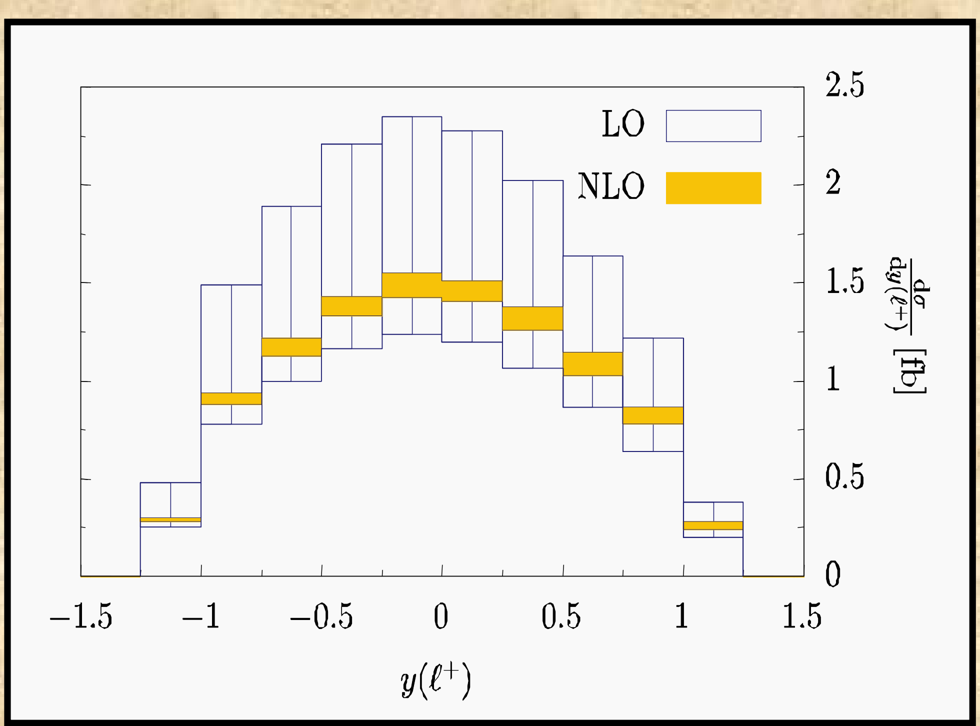
$p_T^{\rm jet} > 15$ GeV $\quad |y^{\rm jet}| < 2$

$p_T^{\rm miss} > 20$ GeV $\quad H_T > 200$ GeV

$\Delta R(j,j) > 0.4 \quad \Delta R(\ell/j,\gamma) > 0.4$

Forward-backward asymmetry

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



$$A_{\rm FB}^{\rm LO}(t\bar{t}\gamma) = -17\%,$$

$$A_{\rm FB}^{\rm NLO}(t\bar{t}\gamma) = -12\%$$