DPF Meeting 2011

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

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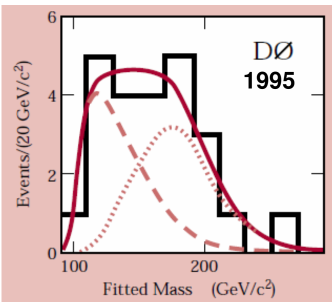
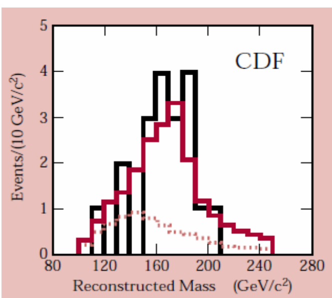
One of Tevatron`s greatest legacy:



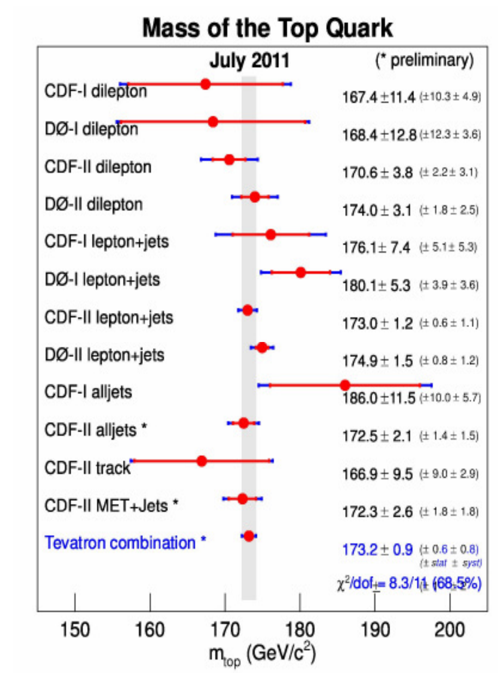


Discovery of the top quark

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, weak charge,

magn./electr. dipole mom., Yukawa coupl.

Electroweak couplings

What do we know about
top quark electroweak couplings ?

electric charge, weak charge,

magn./electr. dipole mom., Yukawa coupl.

This is where the LHC takes over:

$pp \to t\bar{t} + \gamma$

$pp \to t\bar{t} + Z$

$pp \to t\bar{t} + \text{Higgs}$

Studies of $t\bar{t}Z$ and $t\bar{t}\,\text{H}$ 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 .**

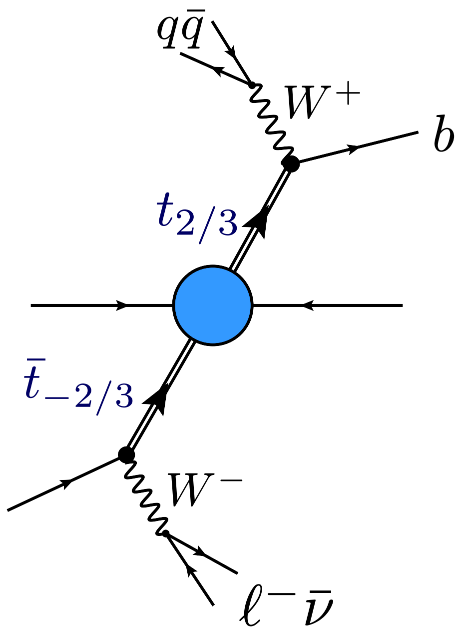
What do we know about the top quark electric charge ?

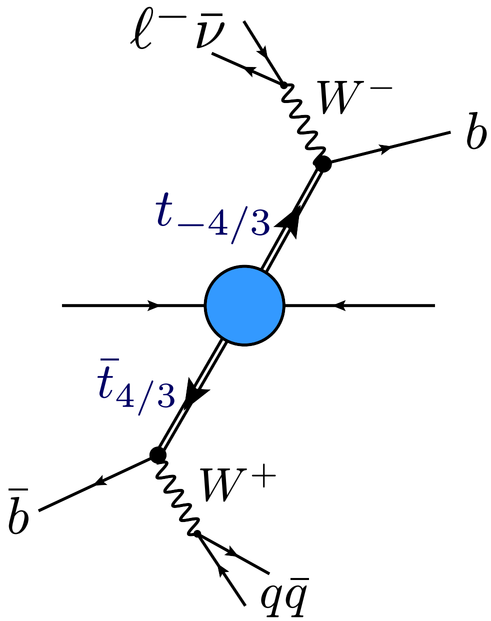
What do we know about the top quark electric charge ?

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

SM

$Q_t = 2/3$





EXOTIC

$Q_t = -4/3$

✓ 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_{top}, M_W)
3) measure b-jet charge (JetCharge Algorithm)

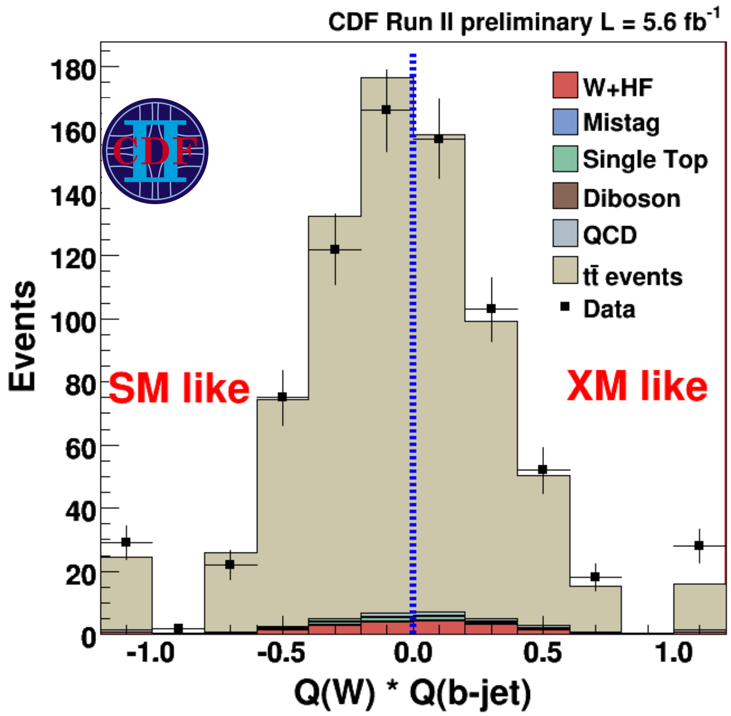
SM top quark charge $\leftrightarrow$ $Q(W) \cdot Q(\text{bjet}) < 0$

XM top quark charge $\leftrightarrow$ $Q(W) \cdot Q(\text{bjet}) > 0$

result: 416 SM events vs. 358 XM events

$\Rightarrow$ 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

$pp \to t\bar{t} + \gamma$ at the LHC

$t\bar{t}$ pairs in association with a photon

$pp \rightarrow t\bar{t} + \gamma$ **at the LHC**

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

Charge measurement is mainly a counting experiment.

NLO normalization is important!

LHC: high energy+luminosity ⇨ expect ~1000 events from 10 fb^{-1}

dominance of gluon flux ⇨ few photons from ISR ($\not\sim Q_{top}$)

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.

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

$2 \to 7$ process is complicated at NLO QCD.

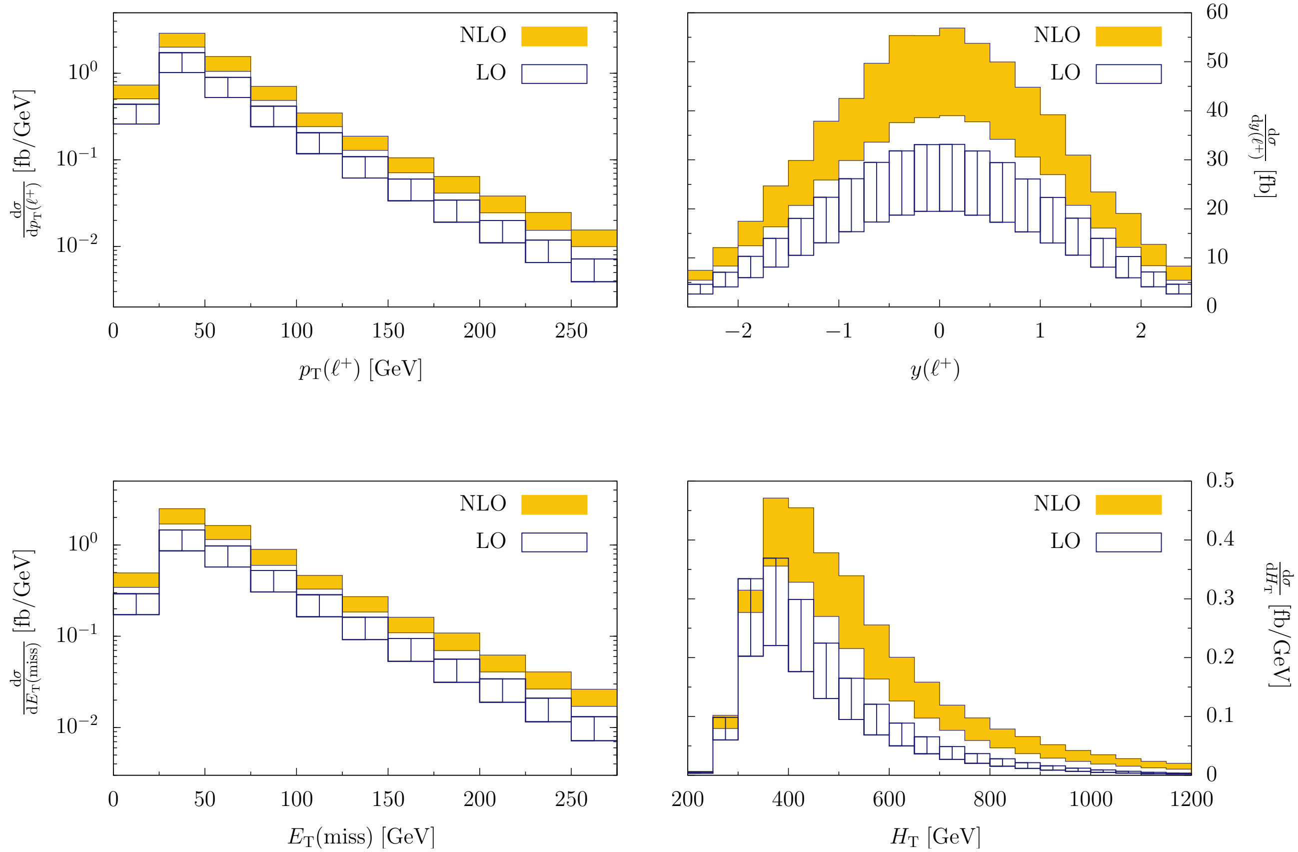
What is important?

- 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
  $\Rightarrow$ *narrow width approximation*
  valid up to $\mathcal{O}(\alpha_s\,\Gamma/m)$
- neglect shower effects and higher order threshold corrections:
  observables under consideration
  should not be very sensitive

Results



LHC
leptons+jets channel
std. acceptance cuts

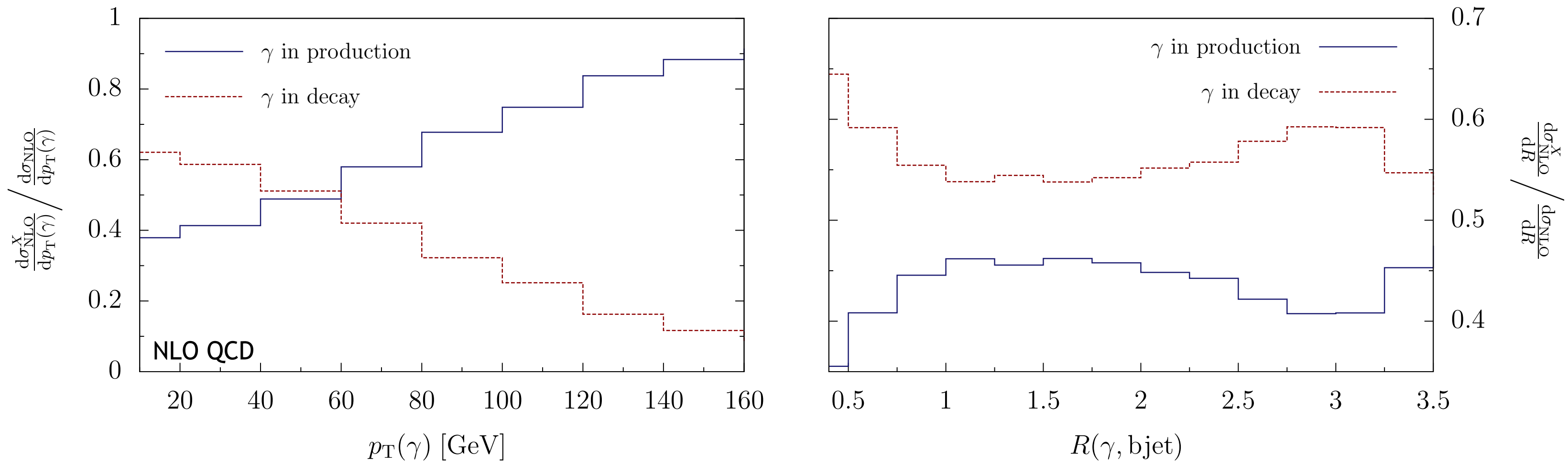
$$\sigma^{\text{LO}}_{t\bar{t}\gamma} = 74.5^{+24.0}_{-16.9}\ \text{fb}$$

$$\sigma^{\text{NLO}}_{t\bar{t}\gamma} = 138^{+30}_{-23}\ \text{fb}$$

- large K-factor ~1.9
- no reduction of scale dependence (opening up of *q*-*g* channel at NLO)

Results

Important:
A large fraction of events from radiative top decays

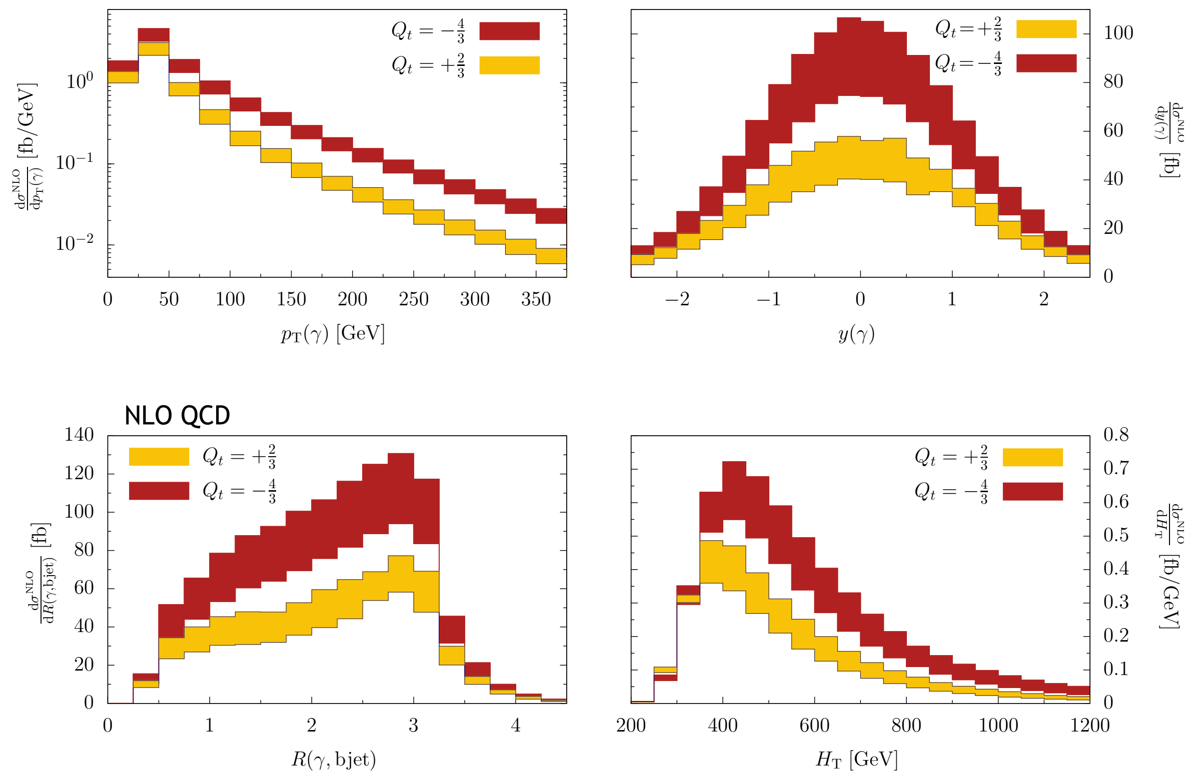


$$\sigma^{\text{decay}}_{t\bar{t}\gamma} = 56\%\ \sigma^{\text{tot}}_{t\bar{t}\gamma}$$

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

Results

Exotic top quarks



$$\sigma^{\text{NLO}}_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t = \frac{2}{3} \to -\frac{4}{3}} \sigma^{\text{NLO}}_{t\bar{t}\gamma} = 243 \text{ fb}$$

Naive expectation of Q_t^2 scaling fails

because of large contribution from radiative top decay

Results

Three strategies:

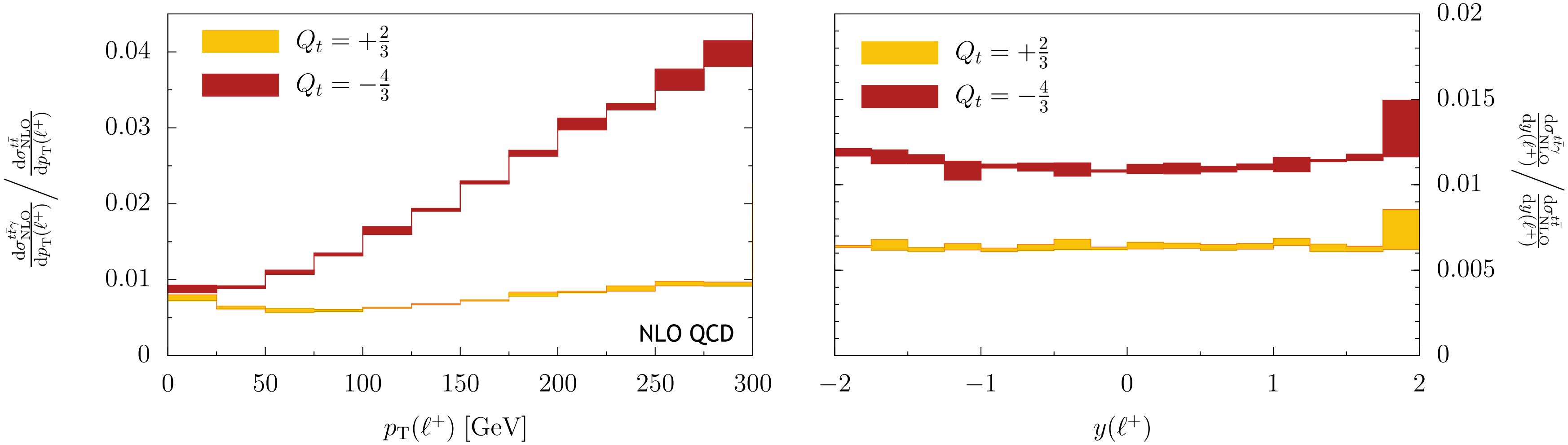
1.) measure the total cross section

2.) study ratio of cross sections

3.) apply cuts to enhance Q_t^2 dependence

Results

2.) Ratio of cross sections $\sigma_{t\bar{t}\gamma} / \sigma_{t\bar{t}}$



$$\frac{\sigma^{Q_t=2/3}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = \begin{cases} 5.66^{+0.03}_{-0.02} \times 10^{-3}, & \text{LO;} \\ 6.33^{+0.26}_{-0.14} \times 10^{-3}, & \text{NLO,} \end{cases} \qquad \frac{\sigma^{Q_t=-4/3}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = \begin{cases} 10.4^{+0.2}_{-0.2} \times 10^{-3}, & \text{LO;} \\ 11.2^{+0.3}_{-0.2} \times 10^{-3}, & \text{NLO.} \end{cases}$$

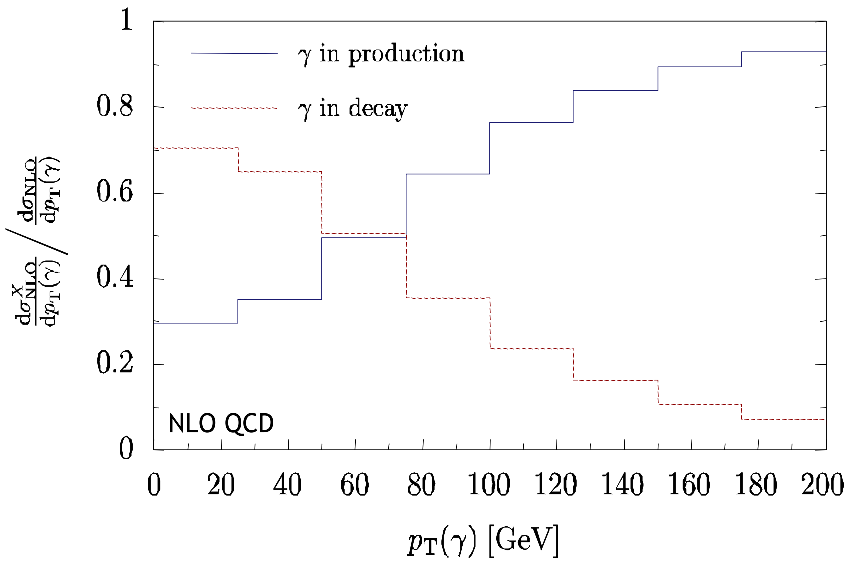
- Ratios are significantly more stable against NLO corrections
- Small scale uncertainties
- Some experimental uncertainties cancel

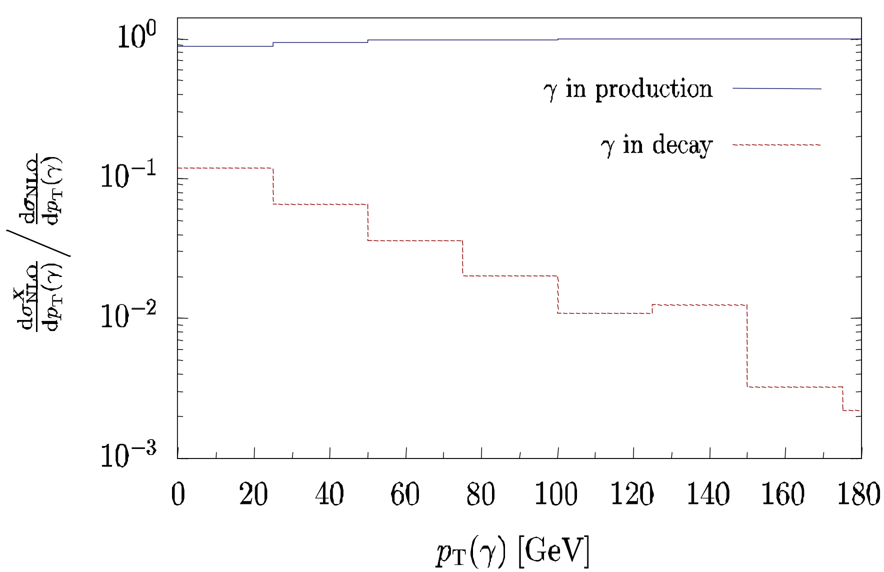
Results

3.) Choose cuts to enhance Q_t^2 dependence

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

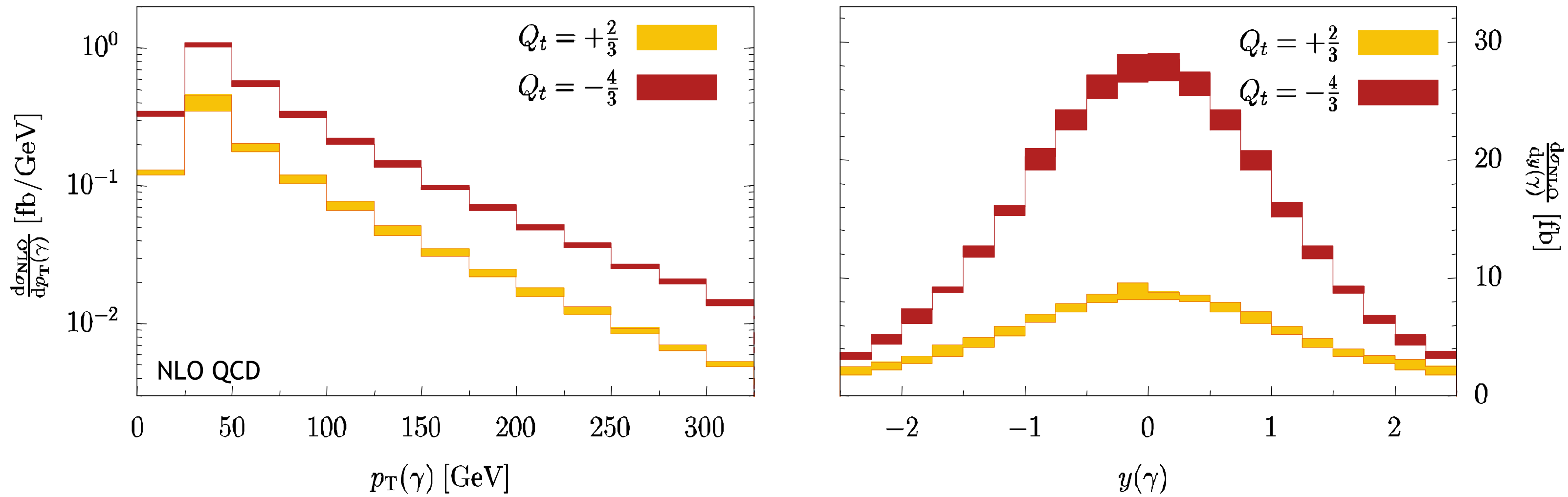
$$m_{\mathrm{T}}(b\ell\gamma; E_{\mathrm{T}}^{\mathrm{miss}}) > 180\ \mathrm{GeV}, \qquad m_{\mathrm{T}}(\ell\gamma; E_{\mathrm{T}}^{\mathrm{miss}}) > 90\ \mathrm{GeV},$$
$$160\,\mathrm{GeV} < m(bjj) < 180\ \mathrm{GeV},\ 70\,\mathrm{GeV} < m(jj) < 90\ \mathrm{GeV}$$





Results

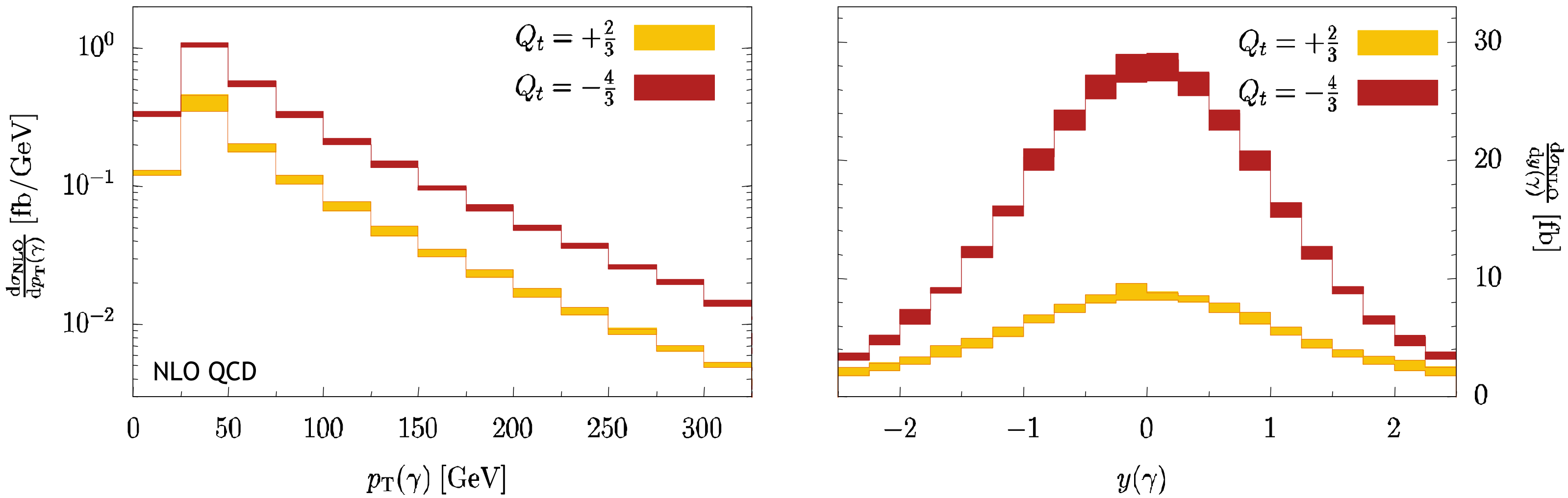
3.) Choose cuts to enhance Q_t^2 dependence



- strong reduction of scale dependence
  smaller K-factor
- enhanced Q_t dependence

Results

3.) Choose cuts to enhance Q_t^2 dependence

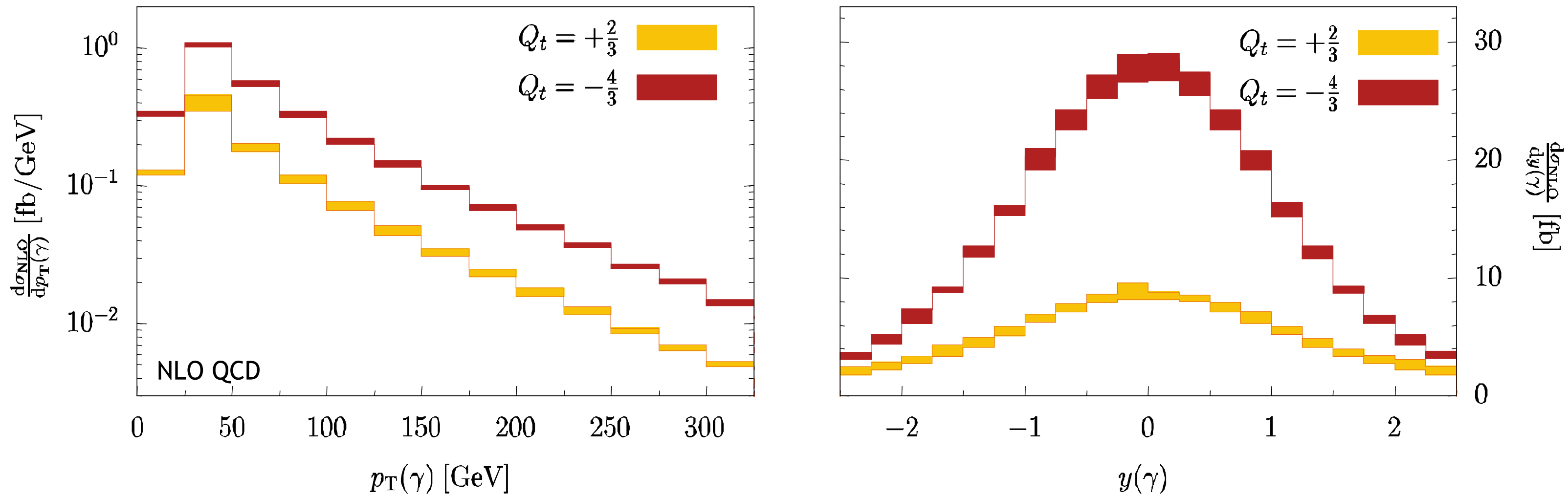


- strong reduction of scale dependence
  smaller K-factor
- enhanced Q_t dependence

However:
- much smaller cross section
  $\sigma^{\text{nocuts}}_{\text{SM}\, t\bar{t}\gamma} = 138\,\text{fb} \Rightarrow \sigma^{\text{cuts}}_{\text{SM}\, t\bar{t}\gamma} = 26\,\text{fb}$

Results

3.) Choose cuts to enhance Q_t^2 dependence



luminosity $\mathcal{L}$ to separate SM and XM hypothesis at 3σ 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**

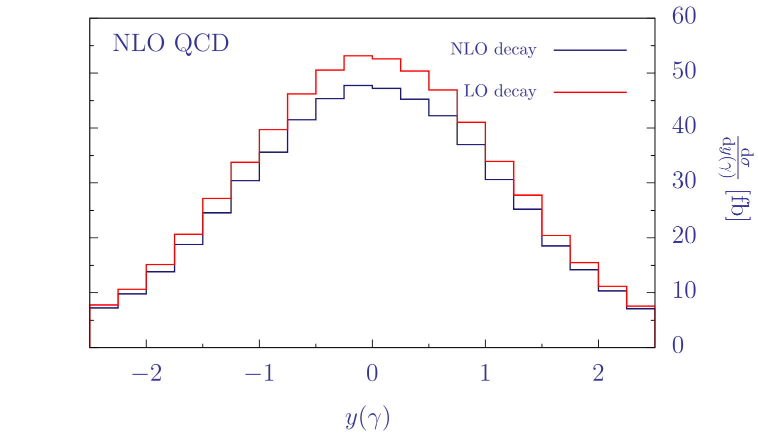
- **large fraction of events from radiative top decays**

- **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

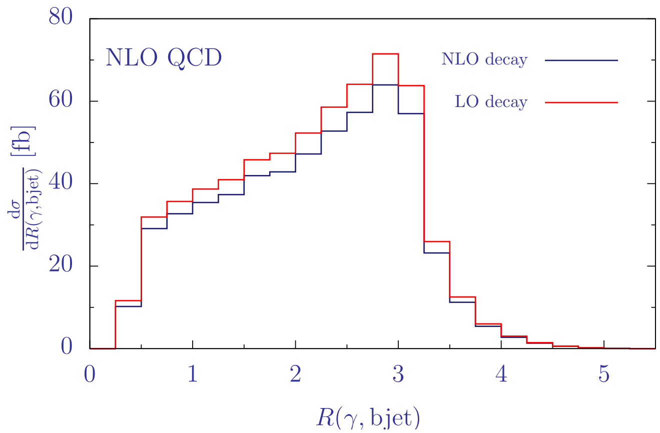
Extras

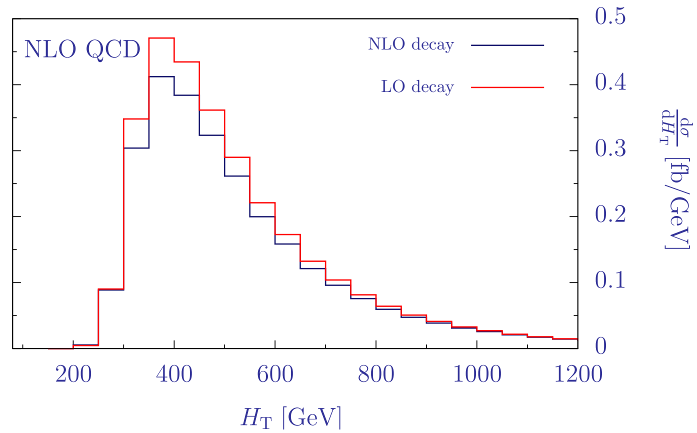
Impact of NLO corrections in the decay



LHC (7TeV)
semi-lept. channel
std. accept. cuts

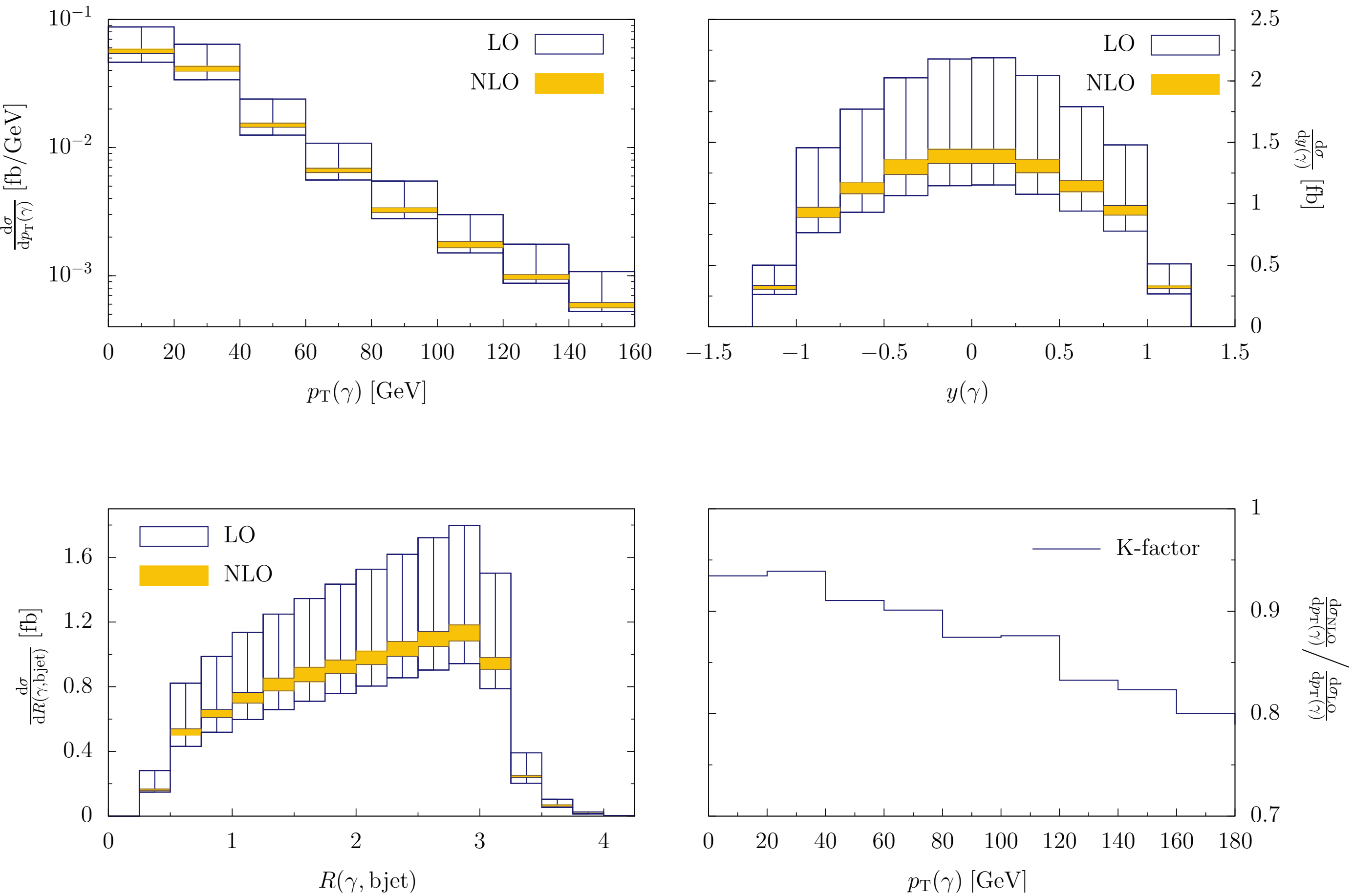
-13% to total cross section





Extras

Tevatron results



$$\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} = 2.85^{+1.14}_{-0.75}\ \mathrm{fb}$$

$$\sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 2.64^{+0.21}_{-0.03}\ \mathrm{fb}$$

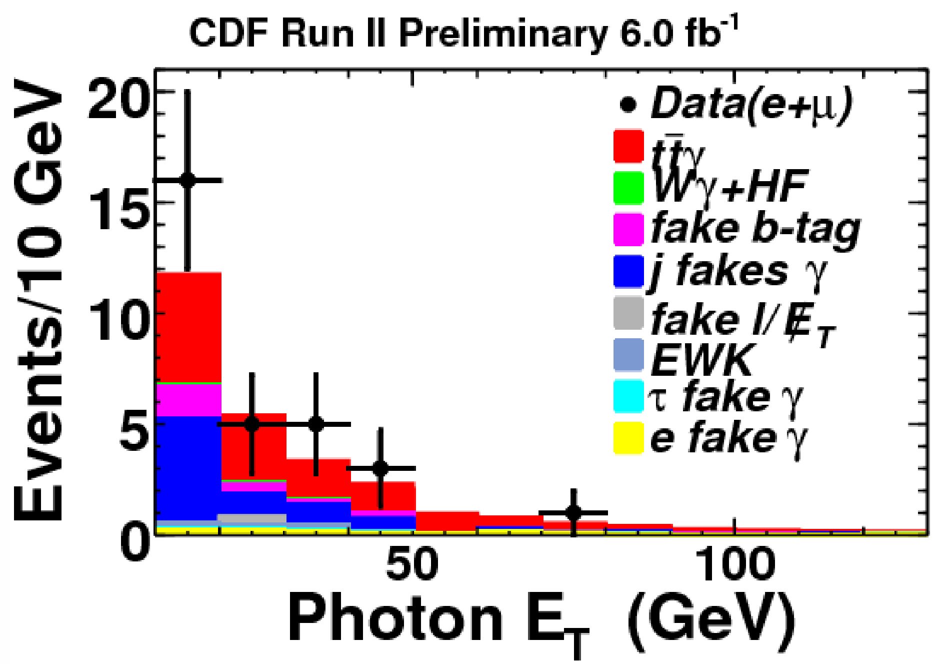
$$\sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 2.64\ \mathrm{fb} \xrightarrow[\times \text{efficiencies} \times 4]{\mathcal{L}_{\mathrm{int}} = 6.0\ \mathrm{fb}^{-1}} 14 \pm 1 \text{ events} \quad \text{vs.} \quad \textbf{CDF:}\ 14 \pm 3 \text{ events}$$

(LO: 16±5 events)

Extras

Tevatron results

CDF Run II, 6.0 fb^{-1}			
$t\bar{t}\gamma$, Isolated Leptons, Tight Chi2 on Photons			
Standard Model Source	$e\gamma b\not{E}_T$	$\mu\gamma b\not{E}_T$	$(e+\mu)\gamma b\not{E}_T$
$t\bar{t}\gamma$(*semileptonic*)	5.98 ± 1.10	5.21 ± 0.97	11.19 ± 2.04
$t\bar{t}\gamma$(*dileptonic*)	1.47 ± 0.27	1.27 ± 0.24	2.74 ± 0.50
$W^{\pm}c\gamma$	0 ± 0.07	0 ± 0.07	0 ± 0.09
$W^{\pm}c\bar{c}\gamma$	0 ± 0.05	0.05 ± 0.05	0.05 ± 0.07
$W^{\pm}b\bar{b}\gamma$	0.15 ± 0.07	0.06 ± 0.05	0.21 ± 0.08
WZ	0.05 ± 0.05	0.05 ± 0.05	0.09 ± 0.06
WW	0.06 ± 0.03	0.06 ± 0.03	0.11 ± 0.03
Single Top (s-chan)	0.09 ± 0.10	0 ± 0.10	0.09 ± 0.13
Single Top (t-chan)	0.14 ± 0.14	0.13 ± 0.14	0.27 ± 0.19
$\tau \rightarrow \gamma$ fake	0.20 ± 0.08	0.10 ± 0.05	0.29 ± 0.09
Jet faking γ ($ej\not{E}_T b, j \rightarrow \gamma$)	5.75 ± 1.76	1.79 ± 1.56	7.54 ± 2.53
Mistags	1.47 ± 0.37	1.02 ± 0.32	2.50 ± 0.51
QCD(Jets faking ℓ and $\not{E}_T$)	0.38 ± 0.38	0.02 ± 0.020	0.40 ± 0.38
$ee\not{E}_T b$, $e \rightarrow \gamma$	0.94 ± 0.19	–	0.94 ± 0.19
$\mu e\not{E}_T b$, $e \rightarrow \gamma$	–	0.49 ± 0.11	0.49 ± 0.11
Total SM Prediction	$16.7 \pm 2.2(tot)$	$10.3 \pm 1.9(tot)$	$26.9 \pm 3.4(tot)$
Observed in Data	17	13	30



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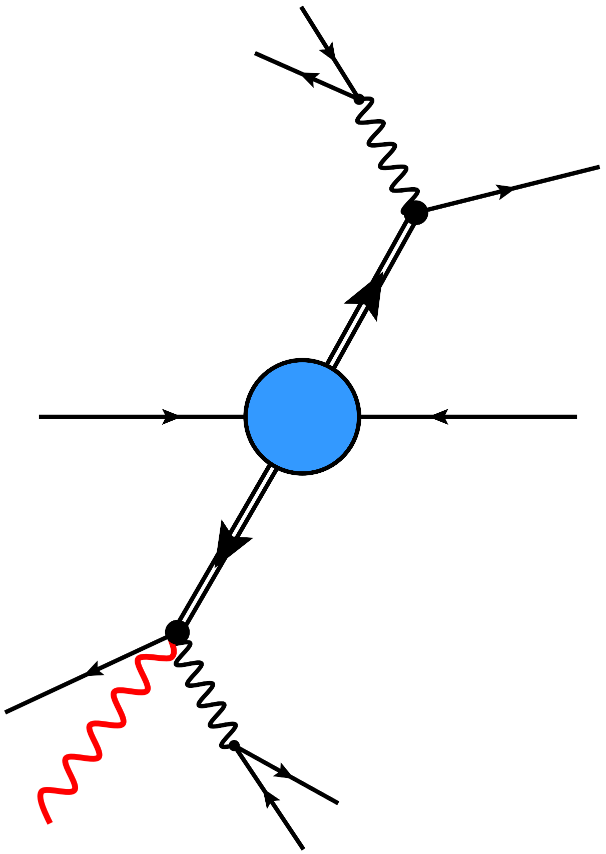
Coupling the photon at NLO

Master formula: $d\sigma \overset{\text{NWA}}{=} d\sigma_{t\bar{t}\gamma}\, d\mathcal{B}_t\, d\mathcal{B}_{\bar{t}} + d\sigma_{t\bar{t}} \left(d\mathcal{B}_{t\gamma}\, d\mathcal{B}_{\bar{t}} + d\mathcal{B}_t\, d\mathcal{B}_{\bar{t}\gamma} \right)$

expand in α_s:

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



Extras

FB asymmetry in ttbar+photon

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

- $t\bar{t}$ asymmetry appears only at NLO QCD [Kühn,Rodrigo]

Theory prediction $A_{\mathrm{FB}}(t\bar{t})=5\%$ in tension with measurement (2σ)

Complete NNLO correction unknown, but indications for robustness

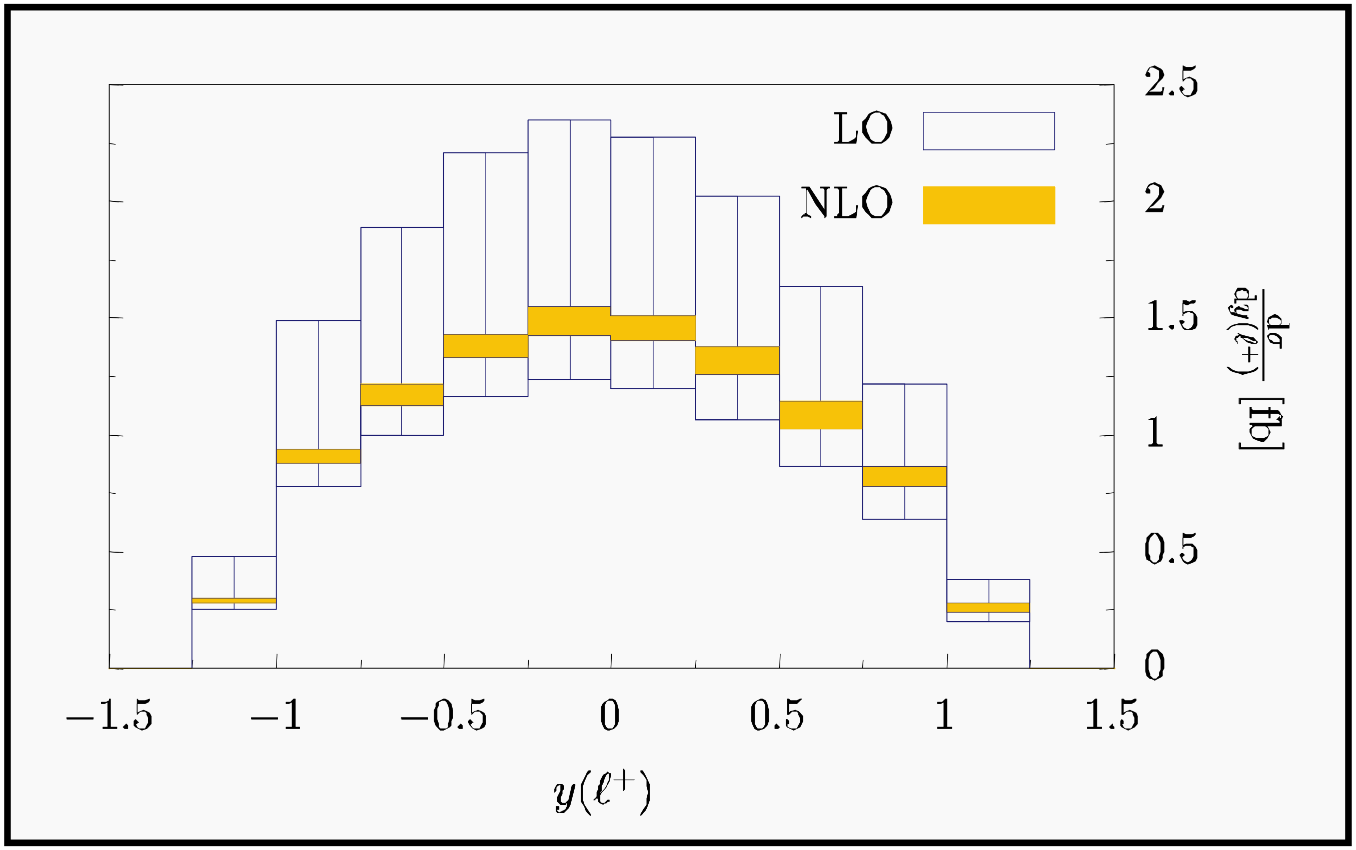
- $t\bar{t}+\gamma$ asymmetry appears already at LO

$A_{\mathrm{FB}}^{\mathrm{LO}}(t\bar{t}\gamma) = -17\%, \quad A_{\mathrm{FB}}^{\mathrm{NLO}}(t\bar{t}\gamma) = -12\%$

The 5% reduction at NLO can be understood. [Melnikov,MS : $t\bar{t}+\mathrm{jet}$]

Similar effect for : $A_{\mathrm{FB}}^{\mathrm{LO}}(t\bar{t}\mathrm{jet}) = -8\%, \; A_{\mathrm{FB}}^{\mathrm{NLO}}(t\bar{t}\mathrm{jet}) = -2\%$

FB asymmetry in ttbar+photon



Extraction of total cross section

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

$$\sigma_{t\bar{t}\gamma} = \sigma^{\text{meas.}}_{b\bar{b}\ell\nu jj\gamma} \times \mathcal{B}(t \to b\ell\nu)^{-1} \times \mathcal{B}(\bar{t} \to \bar{b}jj)^{-1}$$ is wrong.

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

$$\sigma_{t\bar{t}\gamma} = \left(\sigma^{\text{meas.}}_{b\bar{b}\ell\nu jj\gamma} - \sigma^{\text{decay}}_{b\bar{b}\ell\nu jj\gamma}\right) \times \mathcal{B}(t \to b\ell\nu)^{-1} \times \mathcal{B}(\bar{t} \to \bar{b}jj)^{-1} \quad .$$