LoopFest X

Radiative corrections for the LHC and future colliders

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

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in collaboration with K. Melnikov and A. Scharf

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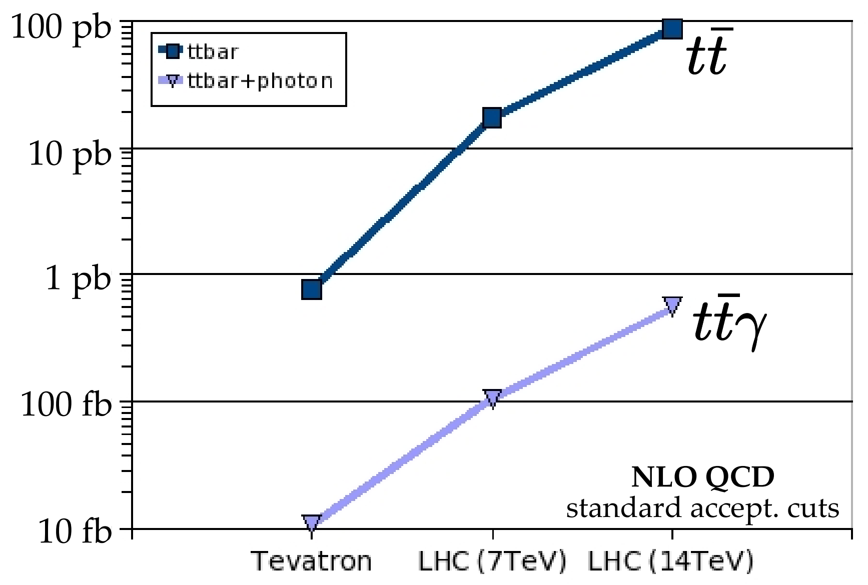
$t\bar{t}$ pairs in association with a photon

cross section for lepton+jets channel



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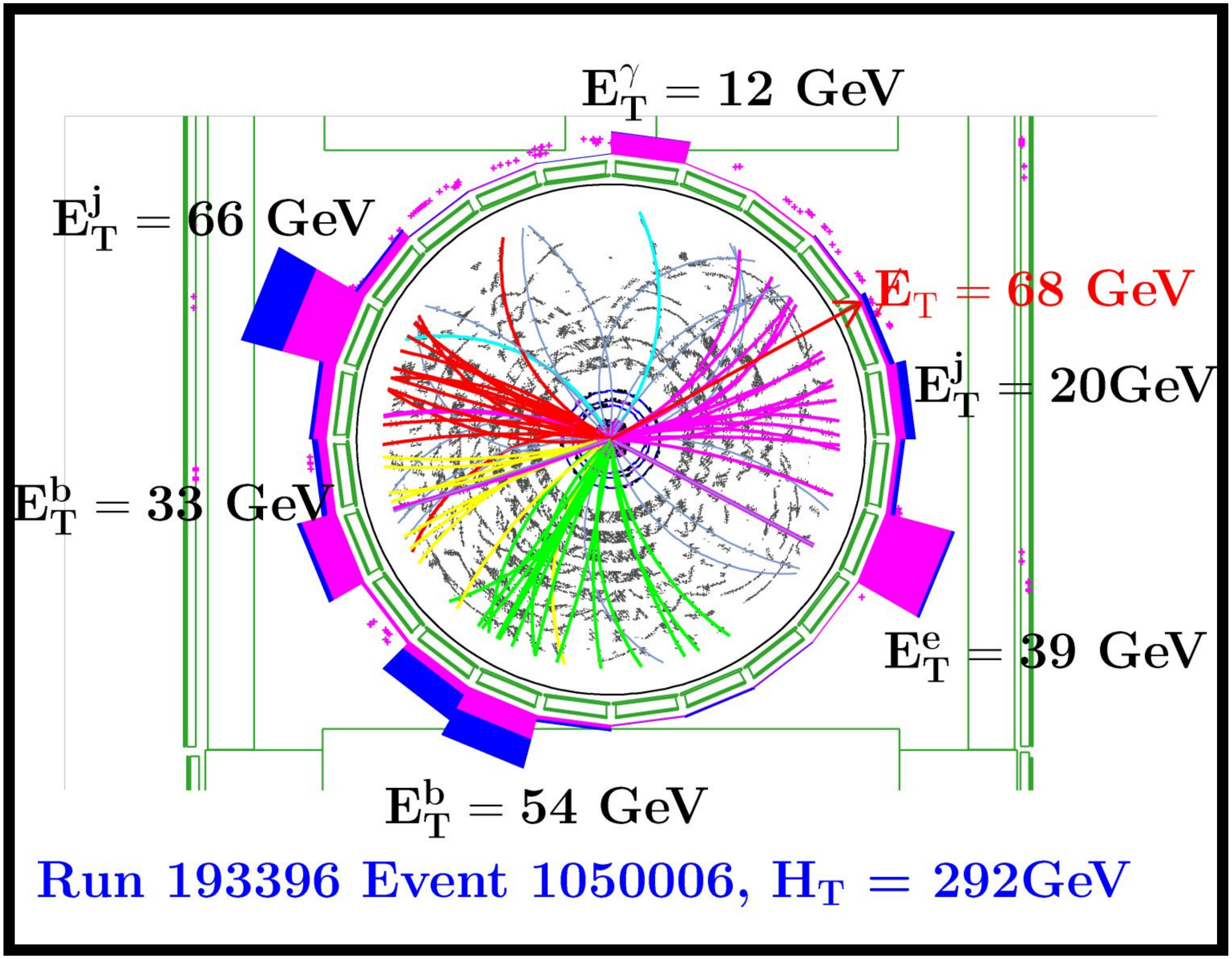

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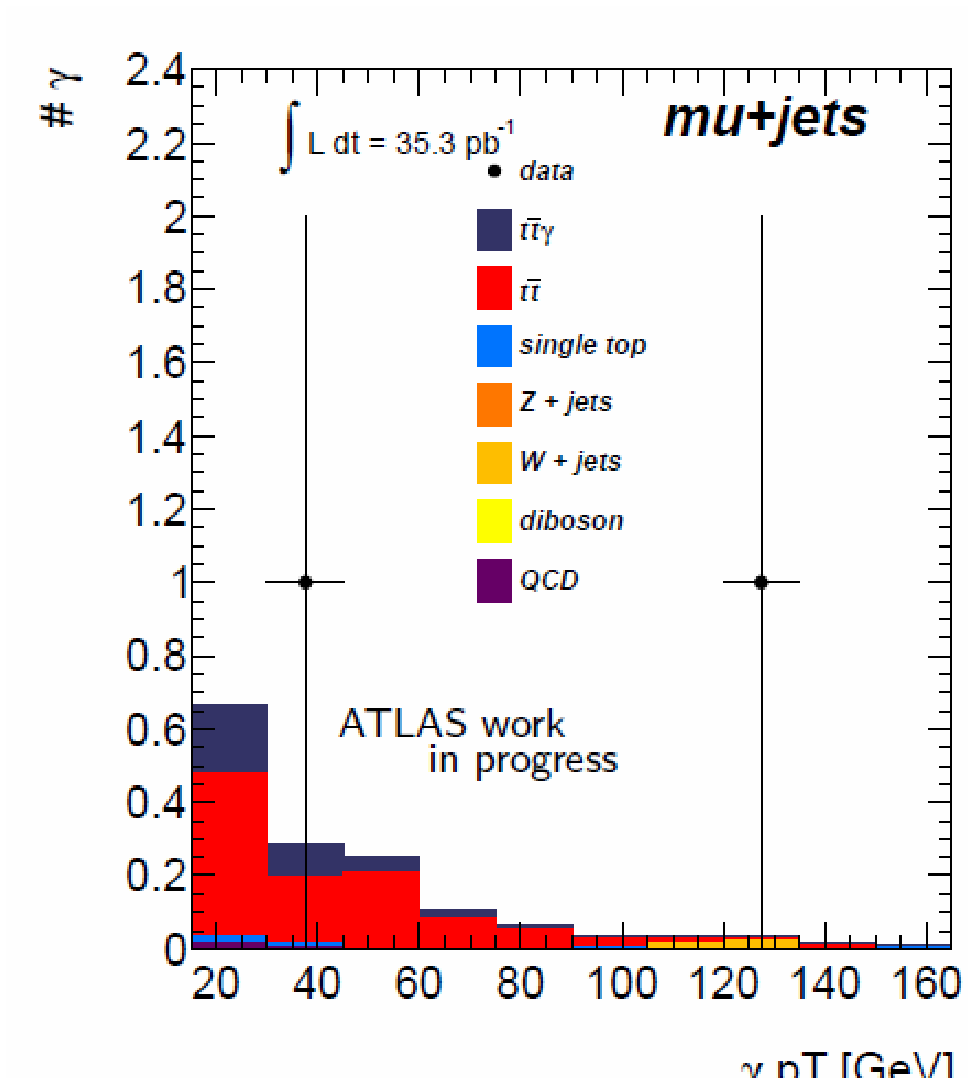
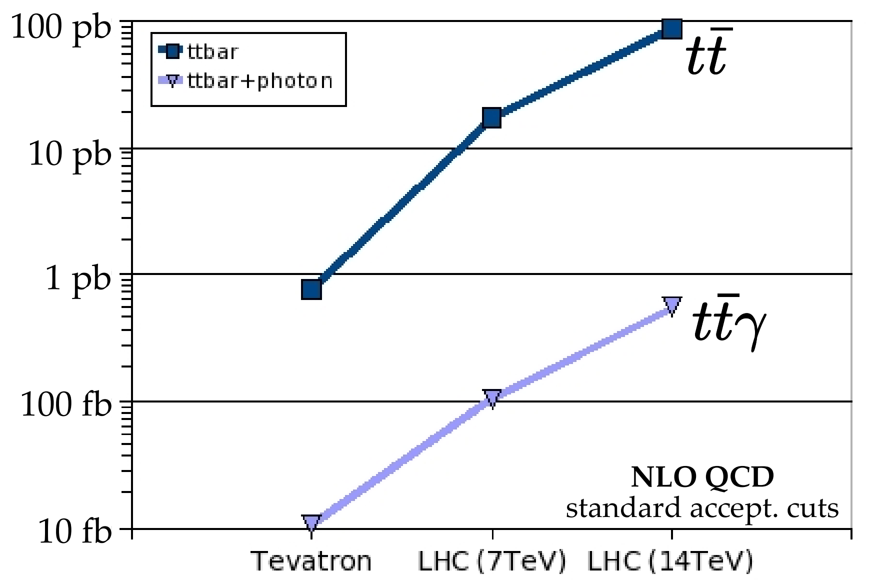


courtesy of I. Fleck et.al. (ATLAS)

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

cross section for lepton+jets channel



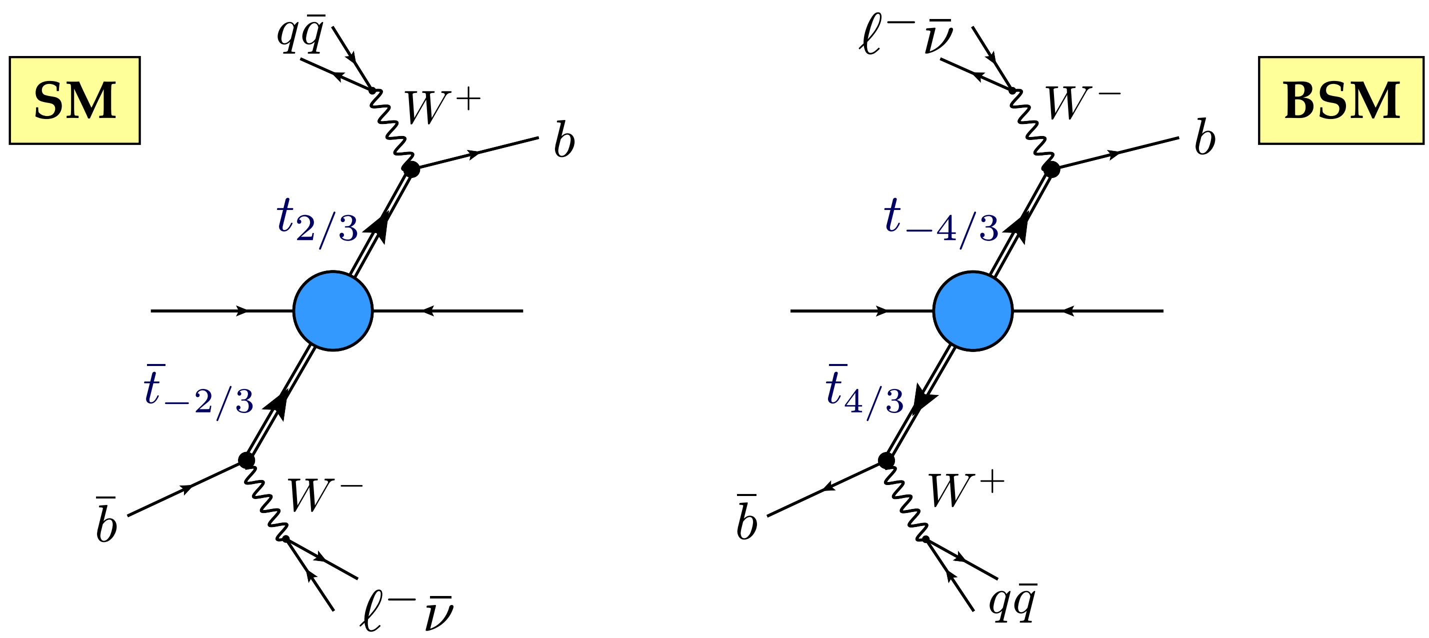
Physics motivation

- measurement of electromagnetic couplings
- forward-backward asymmetry
- control sample for $t\bar{t} + \text{Higgs}$, rare SM process

Top quark electric charge measurement

How well do we know the top quark electric charge?

Until recently, models with an exotic top quark could well describe experimental data.



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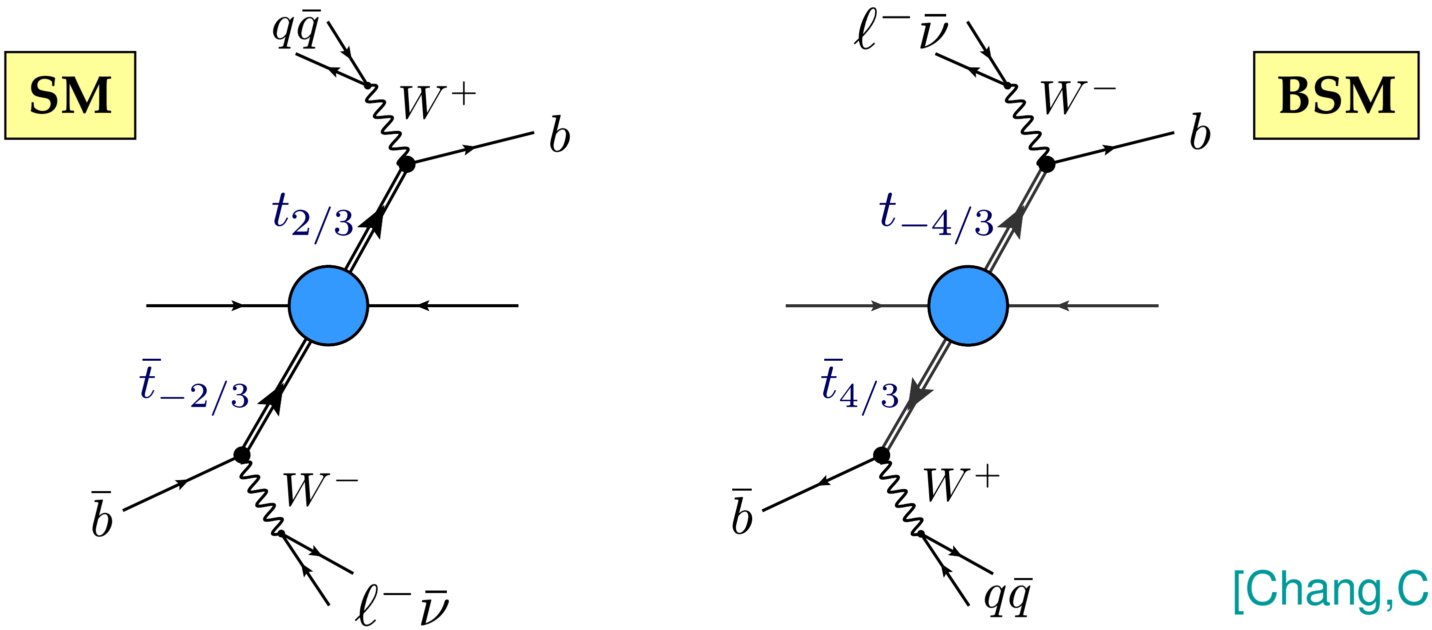


[Chang,Chang,Ma]

$\begin{pmatrix} Q_{4u} \\ Q_{4d} \end{pmatrix}_{\mathrm{R}}$ with el.charges -1/3 and -4/3 + mixing $b_{\mathrm{R}} - (Q_{4u})_{\mathrm{R}}$ + $m_{Q_{4u}} = 172$ GeV, $m_{t_{2/3}} \geq 356$ GeV

✓ electroweak precision tests, ✓ Tevatron searches, ✓ LHC searches

Top quark electric charge measurement

DZero, 370 pb^{-1}: „First determination of the top quark charge“ (2007)

$\Rightarrow$ Fraction of exotic top quarks < 80% at 90% C.L.

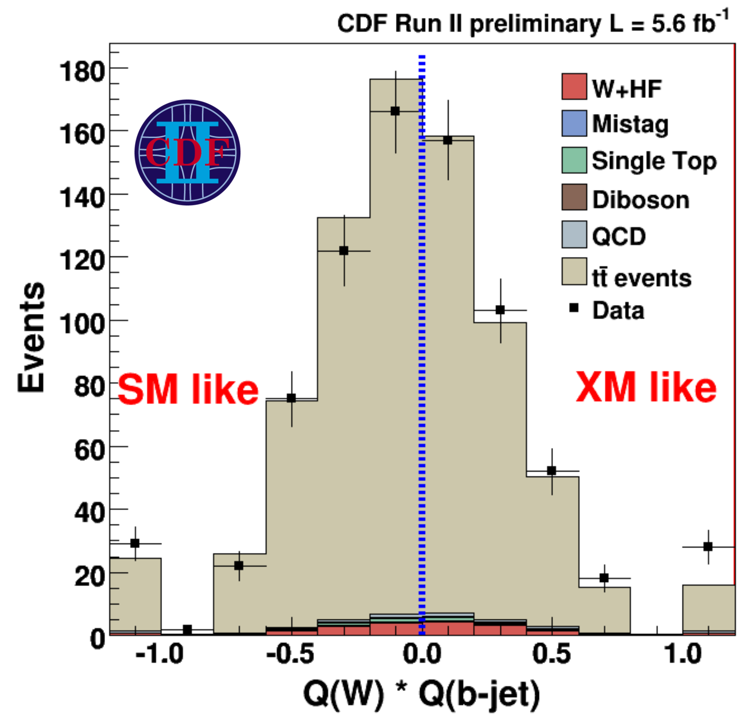
CDF 5.6 fb^{-1} (2011): recent measurement

1) identify W-boson charge through lepton charge
2) pair b-jet with W-boson (topfitter with mt,mW input)
3) measure b-jet charge (JetCharge Algorithm)

assign:

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

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

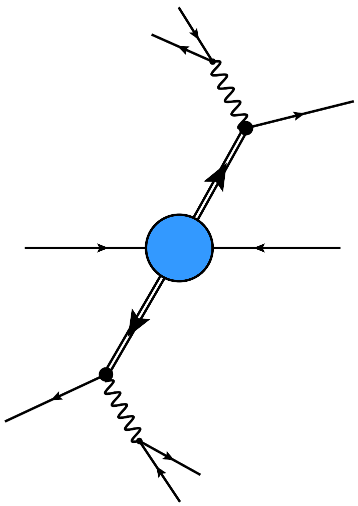


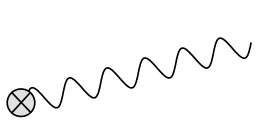
result: 416 SM events vs. 358 XM events

$\Rightarrow$ Exclusion of XM hypothesis with 95% C.L.

Top quark electric charge measurement

How well can we measure Q_t from $t\bar{t}+\gamma$ at hadron colliders?





Photon couples to
all charged particles.

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!

Leading order analysis : Baur,Buice,Juste,Orr,Rainwater (2005, 2007)

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

Top quark electric charge measurement

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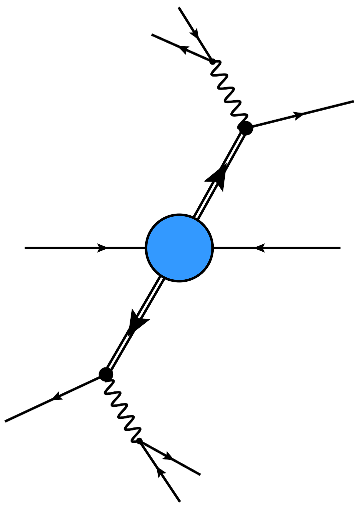

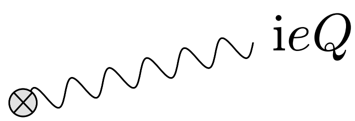

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Next-to-leading order QCD calculation: Duan,Ma,Zhang,Han,Guo,Wang (2009)

- small/large K-factor at the Tevatron/LHC
- stable top quarks

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

We want to realistically describe hadronic production of $t\bar{t}+\gamma$ at NLO QCD.

$pp \to t\bar{t}+\gamma \to b\bar{b}\;\ell\nu\;jj+\gamma$ is a $2 \to 7$ process.

This is very complicated at NLO QCD.

What is important?

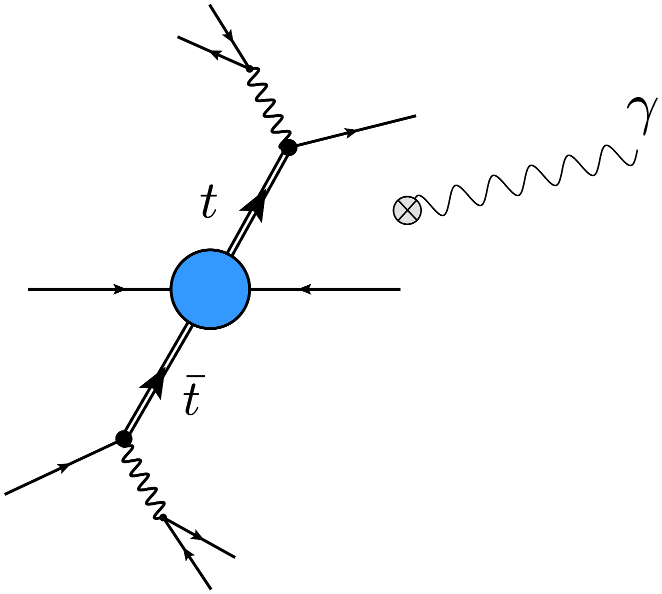
- decays of top quarks:
  realistic final state
- spin correlations:
  acceptances
- photon radiation in decay:
  large contribution
- NLO corrections in production & decay:
  normalization, scale dependence,
  leading soft/collinear emissions

What can be approximated?

- largely off-shell top quarks, W's:
  neglect non-resonant contributions
  $\Rightarrow$ *apply 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

Calculation framework

Top quark decays



- replace top quark on-shell spinors by spinorial currents of the decay process:

$$\bar{u}(p_t) \;\rightarrow\; \bar{\tilde{u}}(p_t) = \mathcal{M}(t \to b\ell^+\nu)\, \frac{\mathrm{i}(\not{p}_t + m_t)}{\sqrt{2m_t\Gamma_t}}$$

- plug this *top decay spinor* into the production process:

$$|\mathcal{M}_{\text{tree}}|^2 = |\bar{\tilde{u}}(p_t)\, \tilde{\mathcal{M}}(ab \to \bar{t}t)\, \tilde{v}(p_{\bar{t}})|^2 \;\; + \mathcal{O}(\tfrac{\Gamma_t}{m_t})$$

- easy to extend to next-to-leading order QCD

[Campbell,Ellis,Tramontano]

Calculation framework

Virtual corrections

- D-dimensional generalized unitarity + OPP reduction [Ellis,Giele,Kunszt,Melnikov] [Ossola,Pittau,Papadopoulos]

Calculation framework

Virtual corrections

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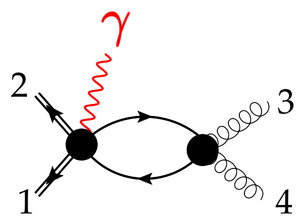
- we obtain primitive amplitudes with photons through linear combinations of gluon primitive amplitudes:

basic idea:



$$\mathcal{A}_f^{[1/2]}(1_{\bar{t}}, 2_t, 5_g, 3_g, 4_g)$$

Calculation framework

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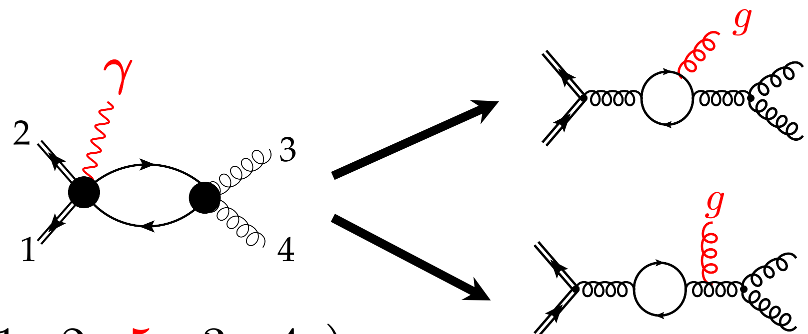

$\mathcal{A}_f^{[1/2]}(1_{\bar{t}}, 2_t, 5_g, 3_g, 4_g)$

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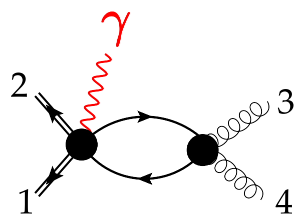
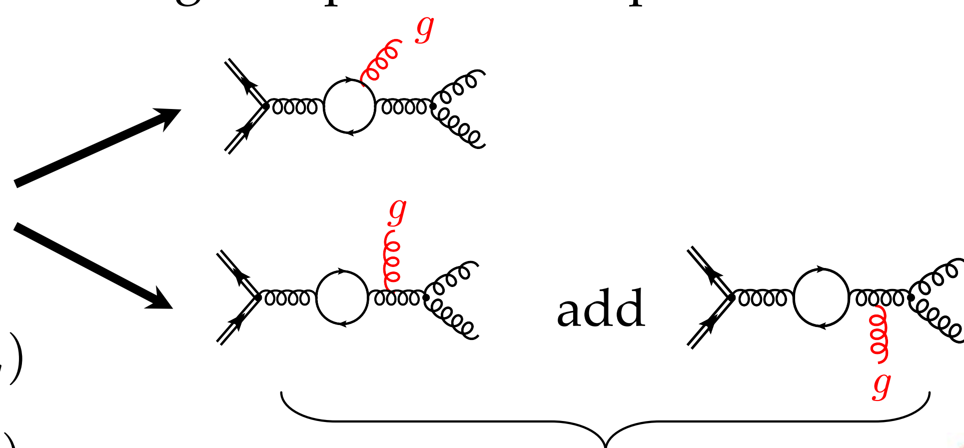
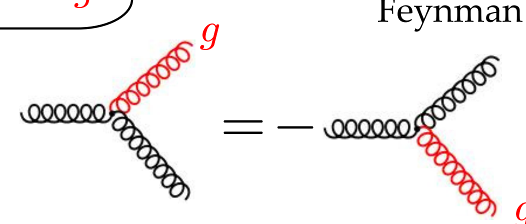




$$\mathcal{A}_f^{[1/2]}(1_{\bar{t}}, 2_t, 5_g, 3_g, 4_g)$$
$$+\mathcal{A}_f^{[1/2]}(1_{\bar{t}}, 2_t, 3_g, 4_g, 5_g)$$

$= 0$ since



color-ordered Feynman rules

Calculation framework

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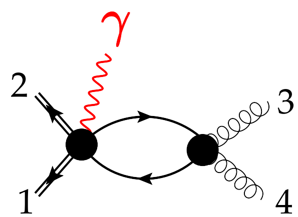

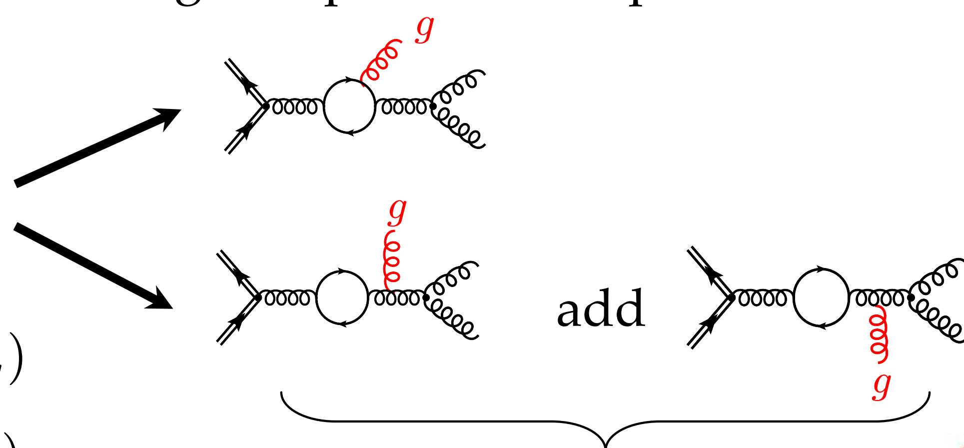

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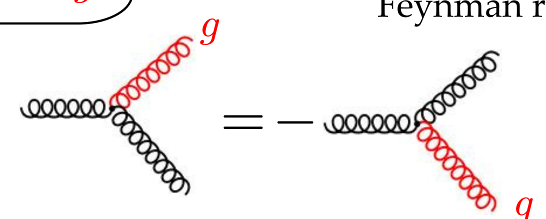

color-ordered Feynman rules

- second independent calculation: OPP applied to Feynman diagrams

Calculation framework

Real corrections

- dipole subtraction with restrictions on resolved dipole phase space (α parameter)

[Catani,Dittmaier,Seymour,Trocsanyi]

[Nagi,Trocsanyi]

[Bevilacqua,Czakon,Papadopoulos,Pittau,Worek]

[Campbell,Ellis,Tramontano]

- dipoles for top decay kinematics [Campbell,Ellis,Tramontano]
  we added α dependence

- all contributions are independent of variations of α

Calculation framework

coupling the photon at NLO

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

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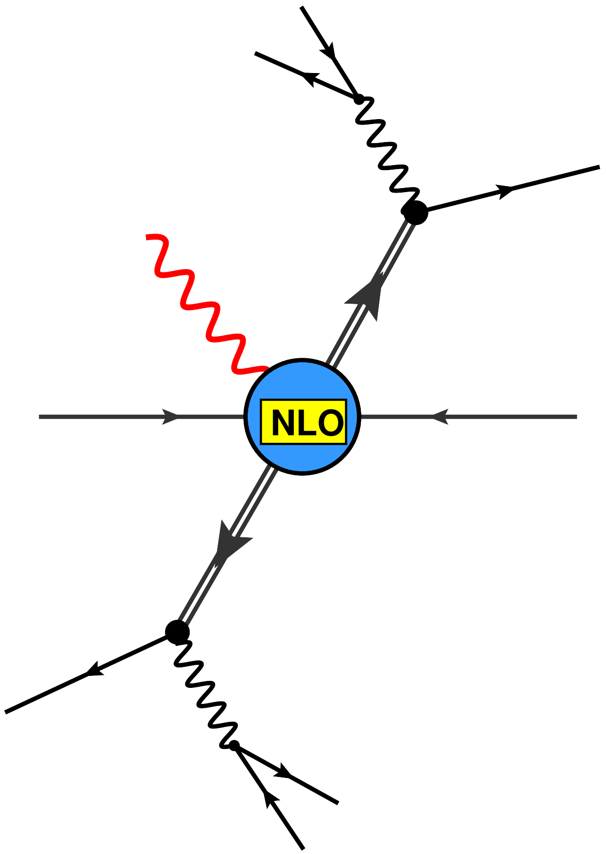
expand in α_s :

$$\mathrm{d}\sigma^{\delta\mathrm{NLO}} = \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}\gamma}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_t\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}}$$



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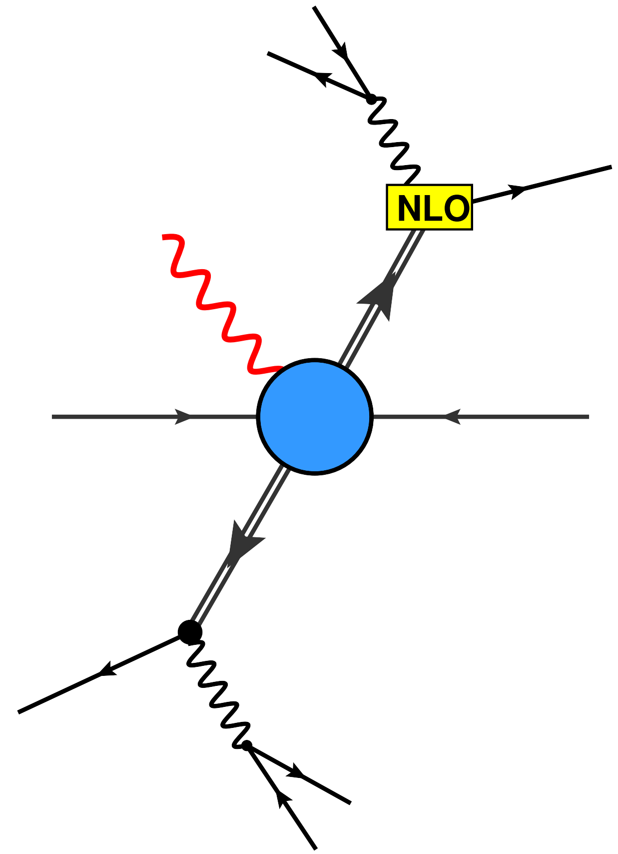
$$+\; \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}\gamma}\left(\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_t\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_t\,\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}}\right)$$



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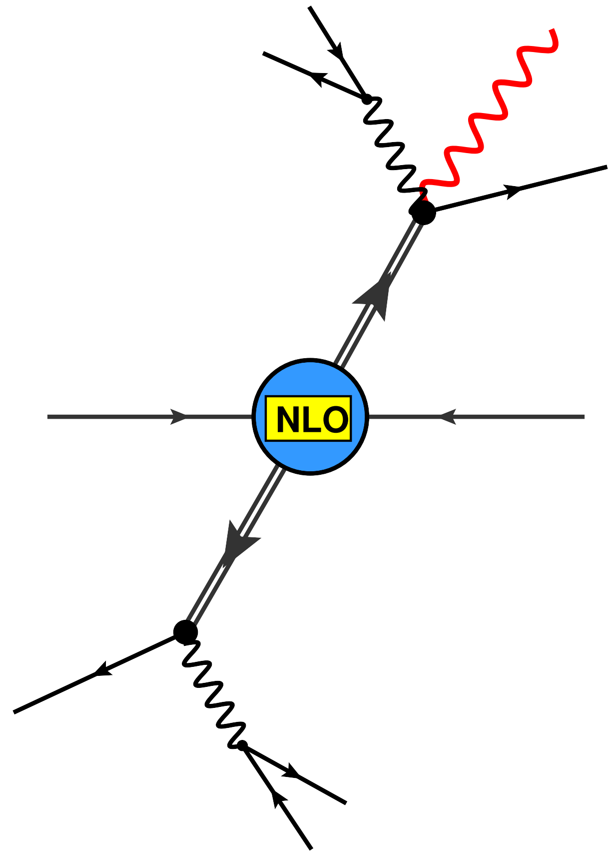

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coupling the photon at NLO

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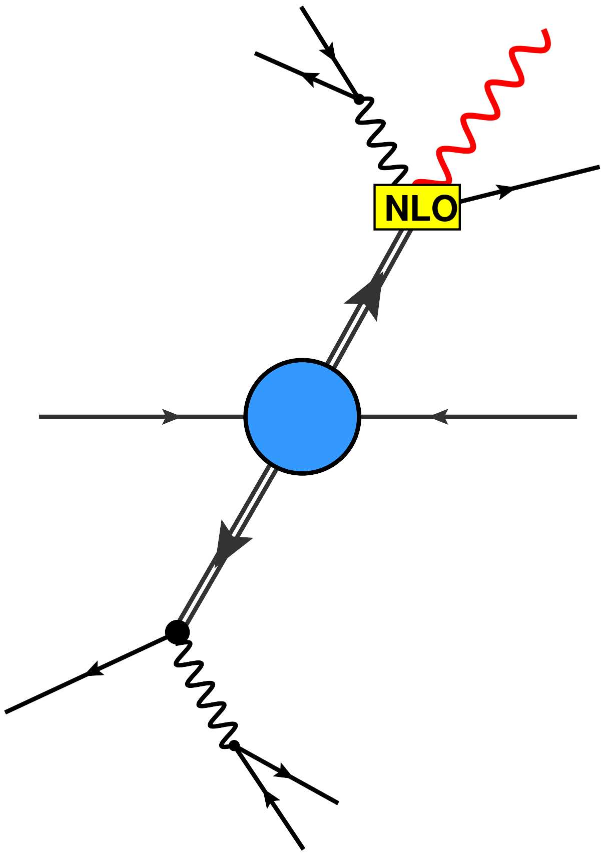

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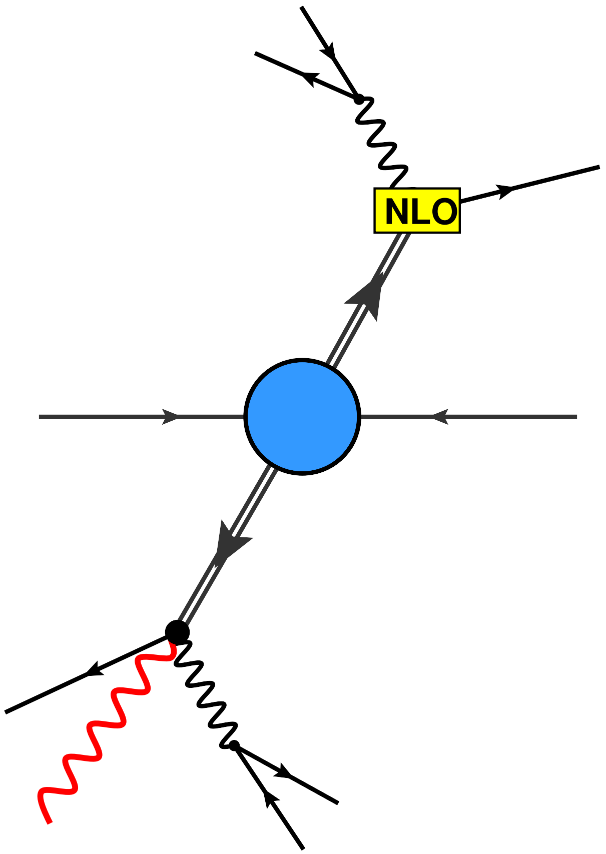
& + \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}}\left(\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\gamma}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_t\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}\gamma}\right) \\
& + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\Big(\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\gamma}\,\mathr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



Results: **Tevatron**

Results: Tevatron

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

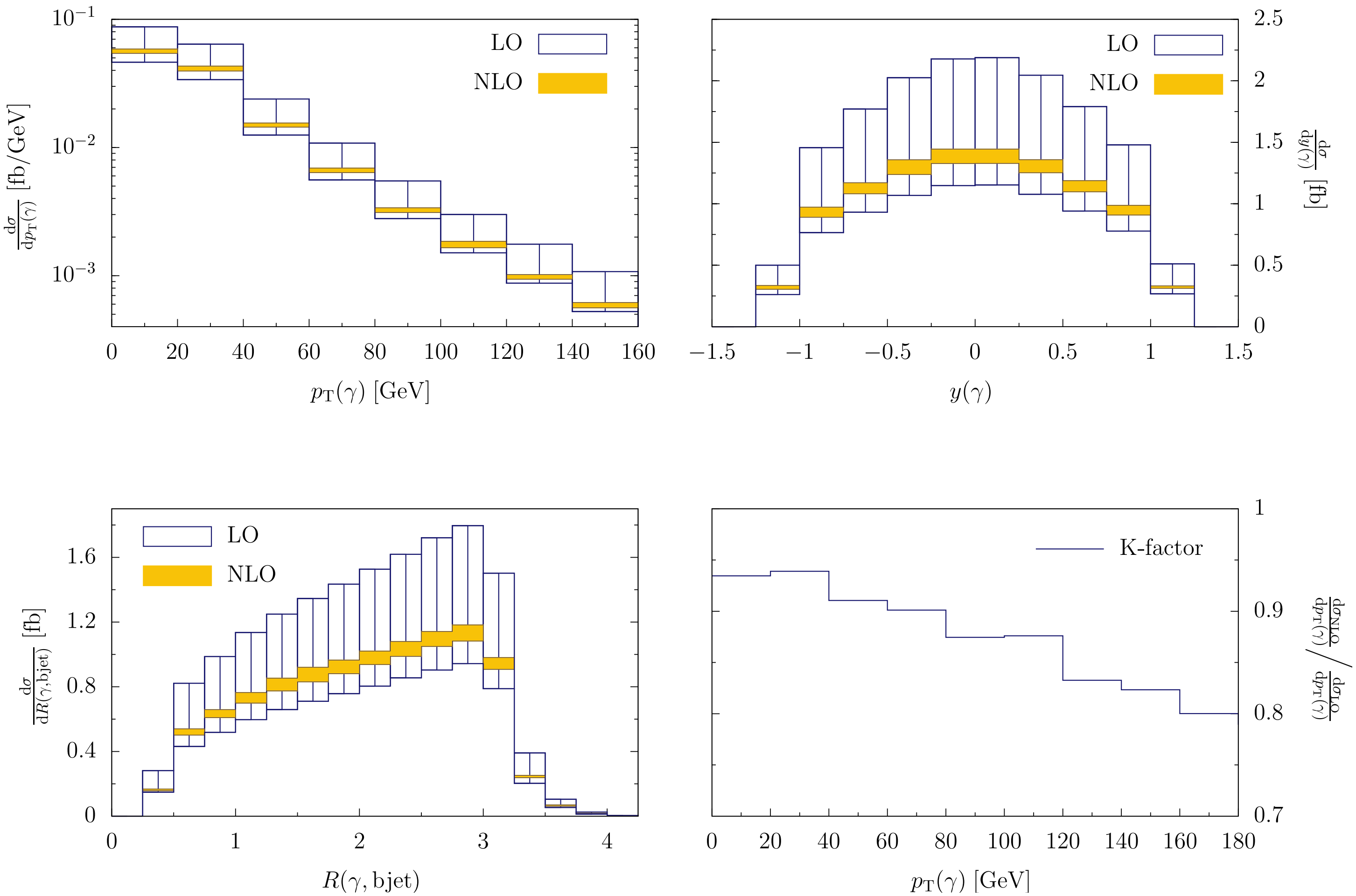
The observable:

$$p_{\mathrm{T}}^{\ell} > 20 \text{ GeV} \qquad |y^{\ell}| < 1.1$$
$$p_{\mathrm{T}}^{\gamma} > 10 \text{ GeV} \qquad |y^{\gamma}| < 1.1$$
$$p_{\mathrm{T}}^{\mathrm{jet}} > 15 \text{ GeV} \qquad |y^{\mathrm{jet}}| < 2$$
$$p_{\mathrm{T}}^{\mathrm{miss}} > 20 \text{ GeV} \qquad H_{\mathrm{T}} > 200 \text{ GeV}$$
$$\Delta R(j,j) > 0.4 \qquad \Delta R(\ell/j,\gamma) > 0.4$$

matches analysis by CDF II ExoTiC

jets: kT jet algorithm
photon: Frixione prescription

Results: Tevatron

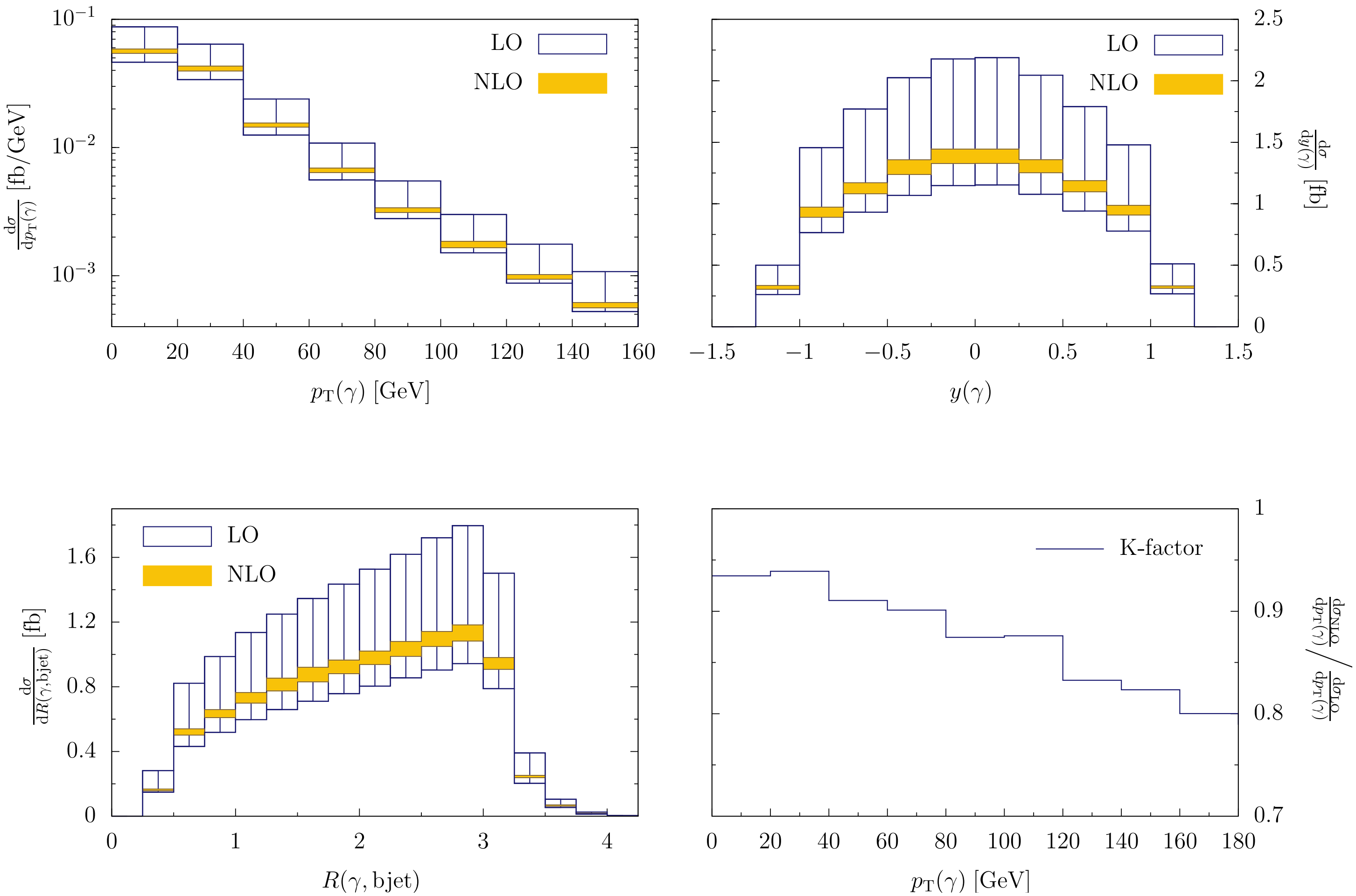


$$\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} = 2.85^{+1.14}_{-0.75}\ \mathrm{fb}$$

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

- significant reduction of scale dependence
- moderate K-factor

Results: Tevatron



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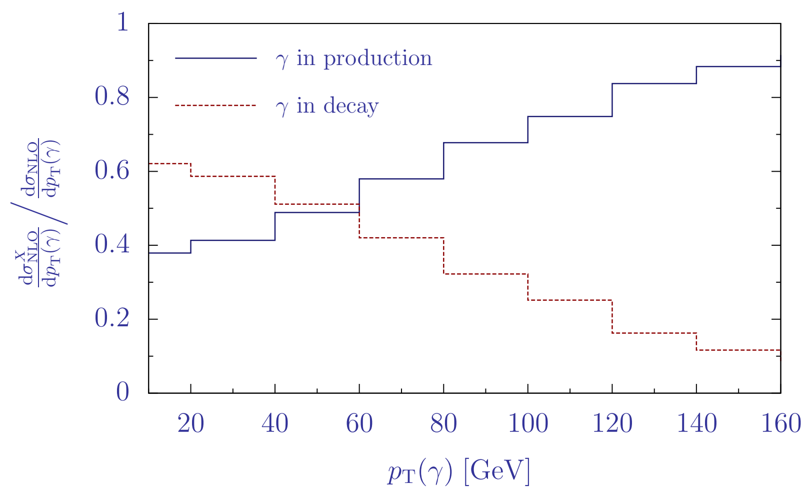
$$\sigma^{NLO}_{t\bar{t}\gamma} = 2.64^{+0.21}_{-0.03} \text{ fb}$$

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

(LO: 16±5 events)

Results: Tevatron

Important: **A large fraction of events from radiative top decays**



$$d\sigma = d\sigma_{t\bar{t}\gamma}\, d\mathcal{B}_t\, d\mathcal{B}_{\bar{t}} \;+\; d\sigma_{t\bar{t}} \left(d\mathcal{B}_{t\gamma}\, d\mathcal{B}_{\bar{t}} + d\mathcal{B}_t\, d\mathcal{B}_{\bar{t}\gamma} \right)$$

$$\boxed{\sigma^{\text{tot}}_{t\bar{t}\gamma} = 2.64\,\text{fb} = (\,1.15\,(\text{prod.}) + \boxed{1.49\,(\text{decay})}\,)\;\text{fb}}$$

$\Longrightarrow$ radiation off decay products is an essential contribution to the cross section (maybe implications for $t\bar{t}$ + jets, $t\bar{t} + b\bar{b}$)

Results: Tevatron

Important: **A large fraction of events from radiative top decays**

$\Longrightarrow$ Implications for extraction of total cross section for „$t\bar{t}\gamma$“.

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.

Results: Tevatron

Important: **A large fraction of events from radiative top decays**

$\Longrightarrow$ Implications for extraction of total cross section for „$t\bar{t}\gamma$“.

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

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

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

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

Results: Tevatron

Forward-backward asymmetry in $t\bar{t}\gamma$

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

- $t\bar{t}$ 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

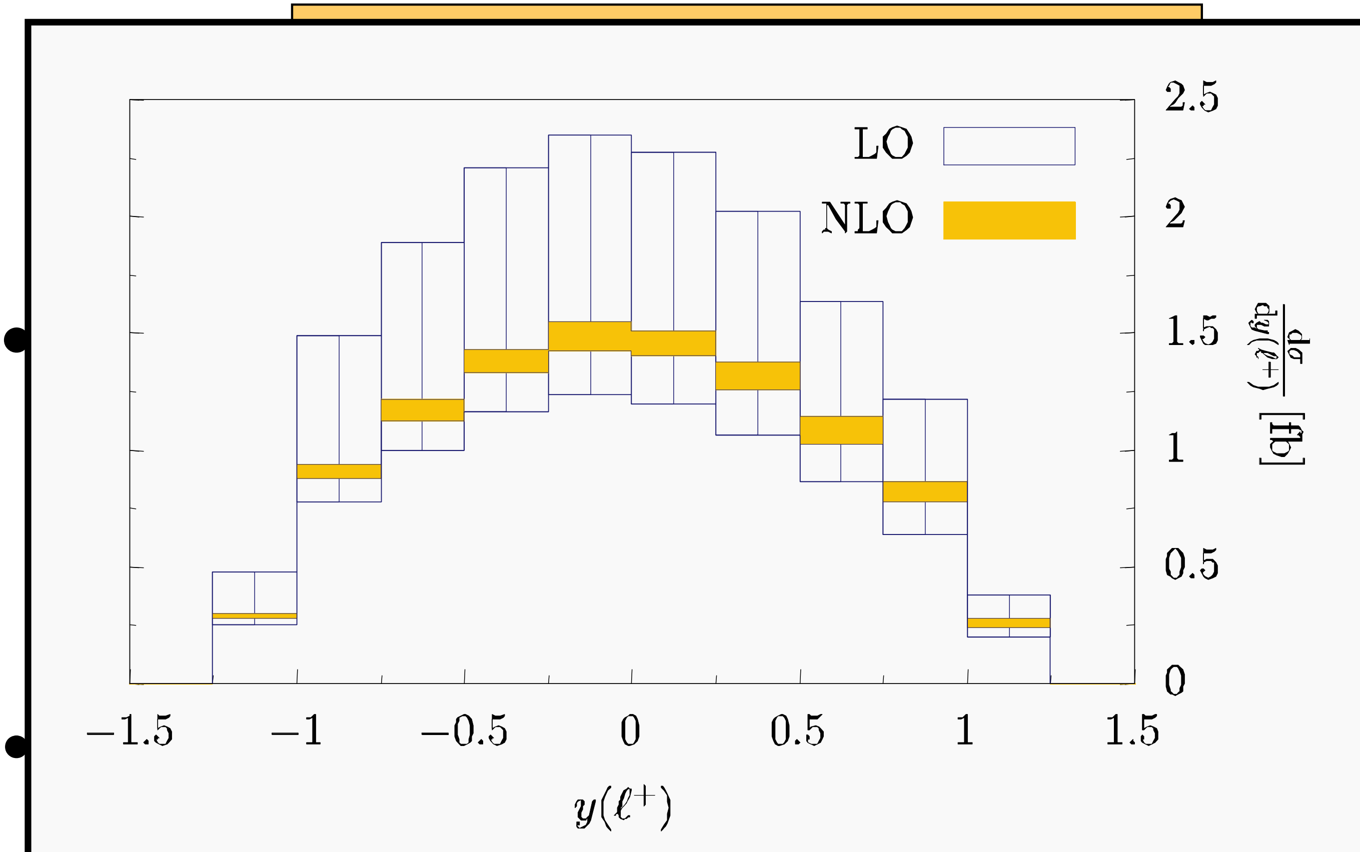
  $A^{\mathrm{LO}}_{\mathrm{FB}}(t\bar{t}\gamma) = -17\%, \quad A^{\mathrm{NLO}}_{\mathrm{FB}}(t\bar{t}\gamma) = -12\%$

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

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

Results: Tevatron

Forward-backward asymmetry in $t\bar{t}\gamma$



[Kühn,Rodrigo]

urement (2σ)

for robustness

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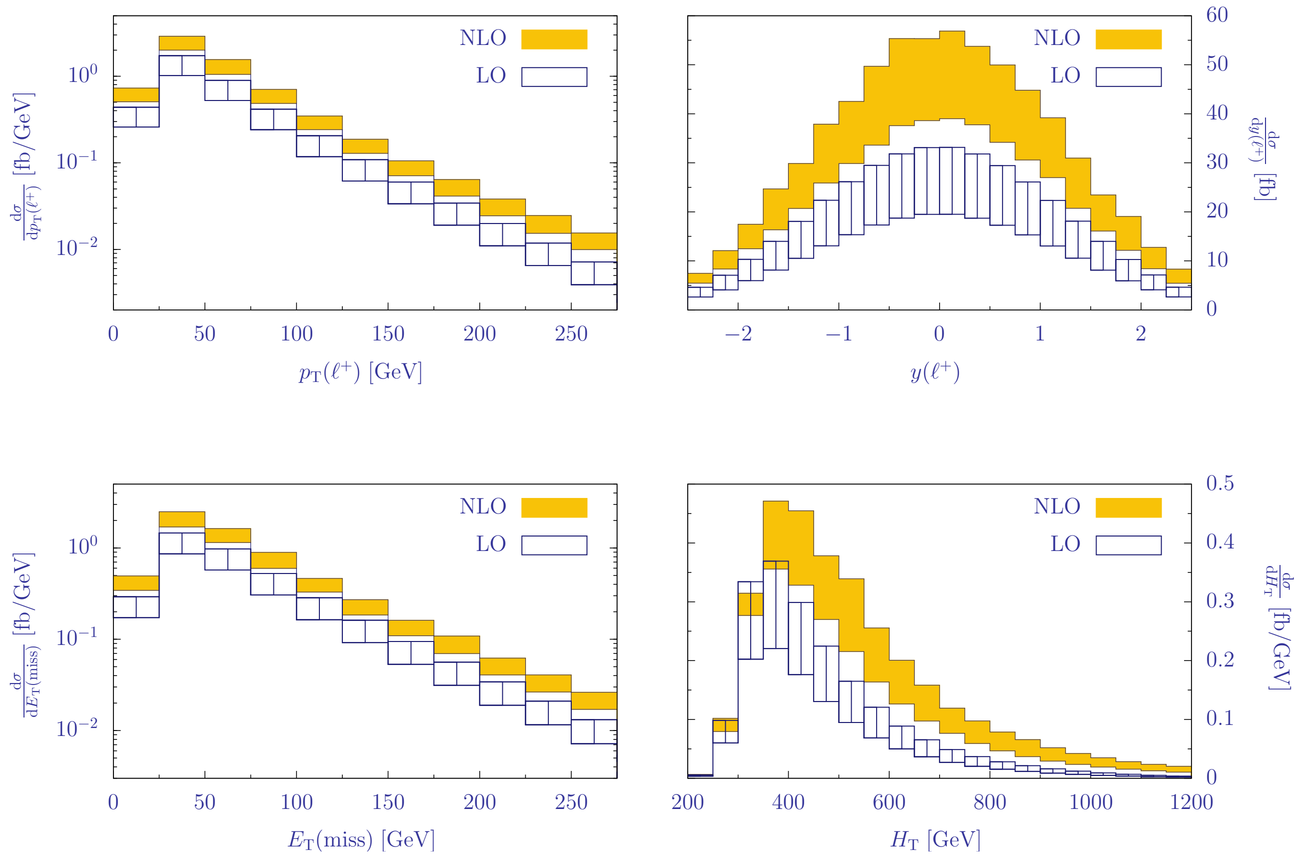
Similar effect for $t\bar{t}$+jet: $A_{\rm FB}^{\rm LO}(t\bar{t}{\rm jet}) = -8\%$, $A_{\rm FB}^{\rm NLO}(t\bar{t}{\rm jet}) = -2\%$

Results: **LHC**

Results: LHC



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

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

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

- large K-factor $\Rightarrow$ extra phase space for additional jet
- no reduction of scale dependence $\Rightarrow$ opening up of q-g channel at NLO

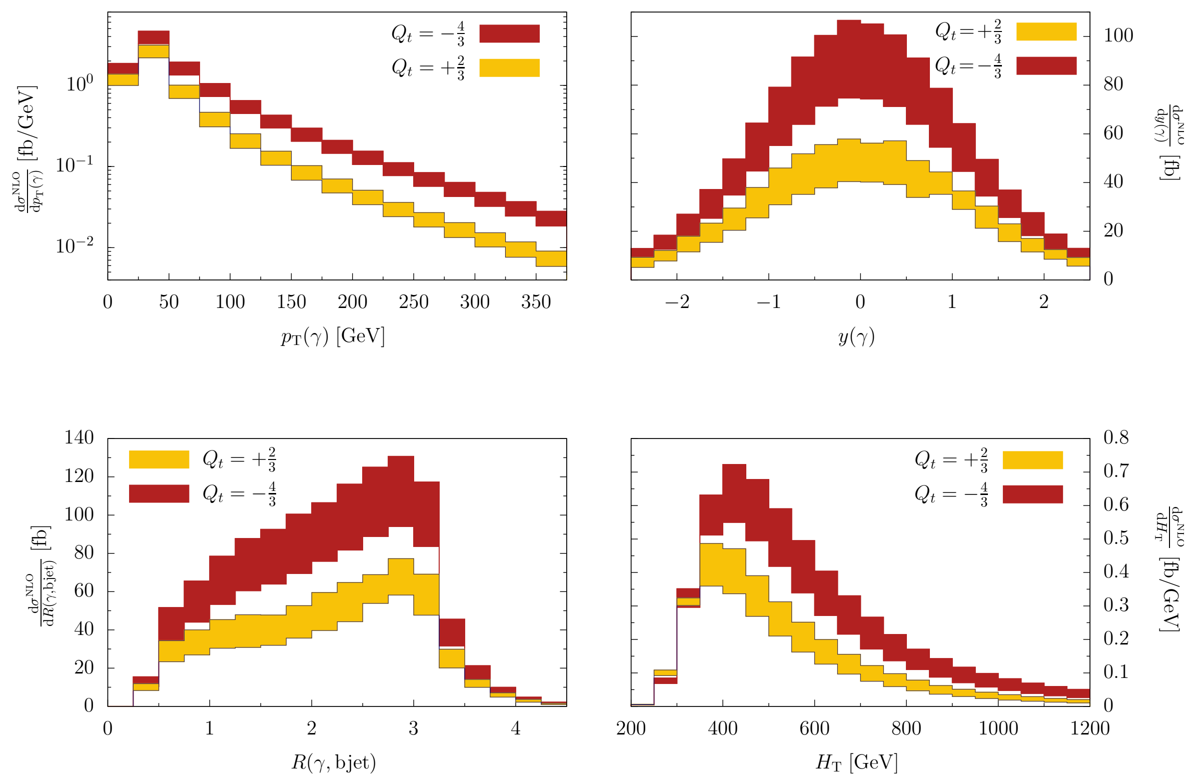
(similar features as in $t\bar{t}$ production)

Results: LHC

Exotic top quarks

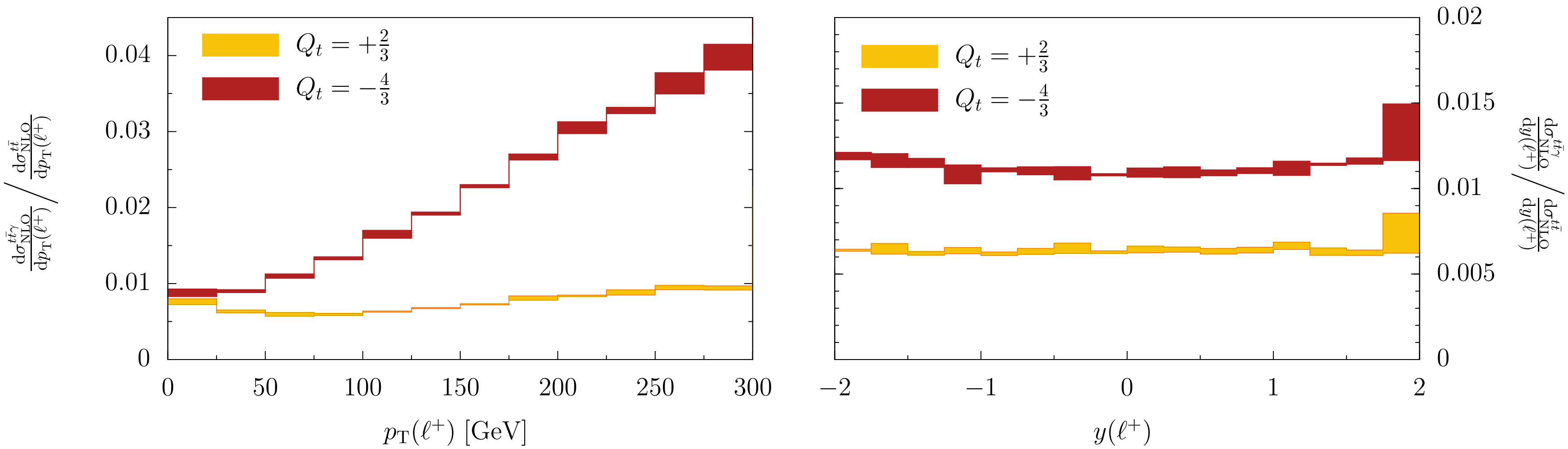
$$\sigma^{\rm NLO}_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t = \frac{2}{3} \to -\frac{4}{3}} \sigma^{\rm NLO}_{t\bar{t}\gamma} = 243 \text{ fb}$$

Large contribution from radiative top decay $\Rightarrow$ Naive expectation of Q_t^2 scaling fails



Results: LHC

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



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

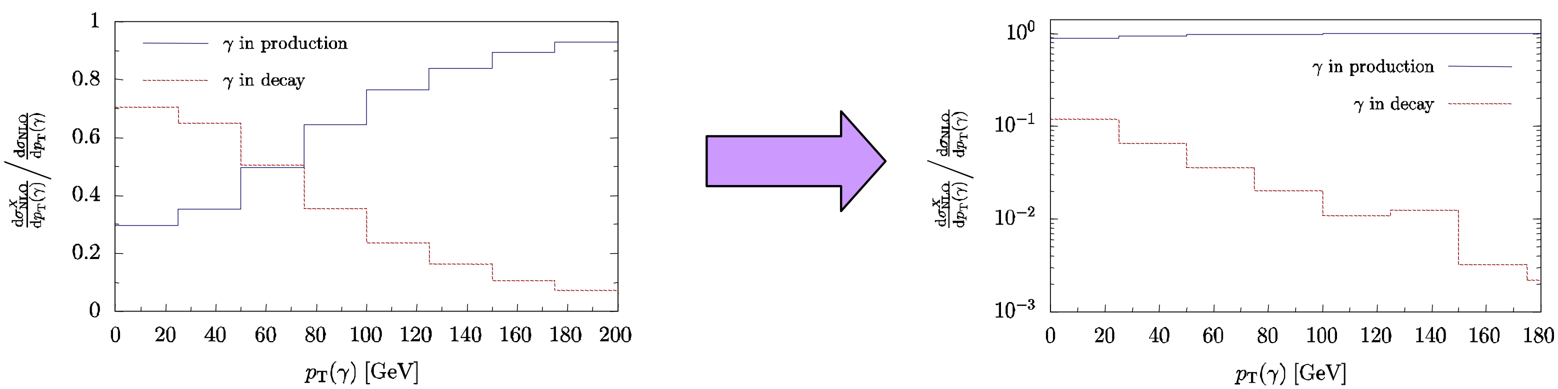
- Ratios are significantly more stable against NLO corrections
- Small scale uncertainties
- Some experimental uncertainties cancel

Results: LHC

2) Choose cuts to enhance Q_t^2 dependence

Inspired by U.Baur et.al.: suppress radiative top decays [Baur,Buice,Orr]

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



Results: LHC

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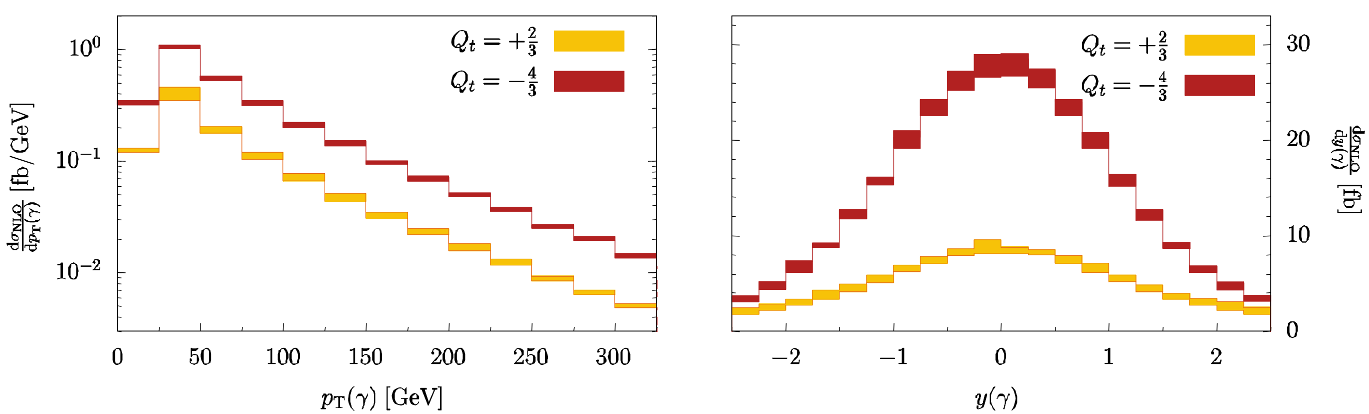


$$\sigma_{t\bar{t}\gamma}^{\mathrm{NLO}} = 26.7^{1.3}_{-2.3}\ \mathrm{fb}$$

improved scaling with Q_t but significantly smaller cross section

(smaller K-factor, strongly reduced scale uncertainty)

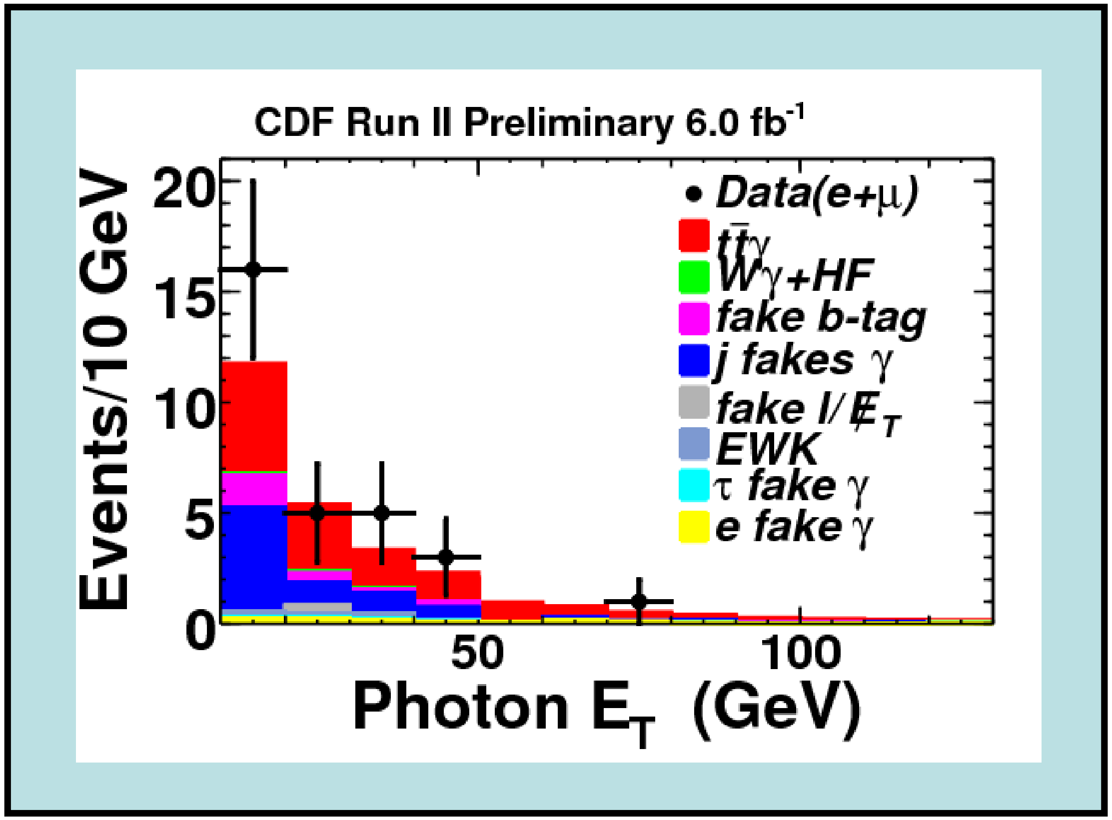
SUMMARY

The process $t\bar{t} + \gamma$ is an interesting SM signal

- We calculated $pp \to t\bar{t} + \gamma \to b\bar{b}\; \ell\nu\; jj + \gamma$ at NLO QCD
  - realistic and flexible setup
  - include top decays and account for all spin correlations
  - allow photon radiation off decay products
- Tevatron: good agreement with CDF measurement
- LHC: possibility to measure electromagnetic couplings of the top quark
- Large contribution from radiative top decays

Extras

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
$\tau \to \gamma$ fake	0.20 ± 0.08	0.10 ± 0.05	0.29 ± 0.09
Jet faking γ $(ej\not{E}_T b, j \to \gamma)$	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
$ee\not{E}_T b$, $e \to \gamma$	0.94 ± 0.19	–	0.94 ± 0.19
$\mu e\not{E}_T b$, $e \to \gamma$	–	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


CDF Run II Preliminary 6.0 fb^{-1}
Events/10 GeV
Photon E_T (GeV)
Data(e+μ)
$t\bar{t}\gamma$
Wγ+HF
fake b-tag
j fakes γ
fake l/$\not{E}_T$
EWK
τ fake γ
e fake γ
0
5
10
15
20
50
100

We can now estimate if it is worth applying the RDS cuts. We denote by $\mathcal{L}$ the luminosity required to separate $Q_t = -4/3$ from $Q_t = 2/3$ at the 3σ level with the cuts in Eq.(**??**) and by $\mathcal{L}_{\rm RDS}$ the same quantity when the RDS cuts are applied in addition. The two quantities are related by the following equation[1]

$$\frac{\mathcal{L}}{\mathcal{L}_{\rm RDS}} = \frac{\sigma_{\rm RDS}^{Q_t=2/3}}{\sigma^{Q_t=2/3}} \frac{(\mathcal{R}_{\rm RDS}-1)^2}{(\mathcal{R}-1)^2} \tag{1}$$

We can use Eqs.(**??**,**??**,**??**,**??**,**??**,**??**) to compute the ratio of the required luminosities at leading and next-to-leading order in perturbative QCD. Interestingly, because the K-factors for the two types of cuts are so different, we find that the required ratios of luminosities differ by a significant amount

$$\frac{\mathcal{L}}{\mathcal{L}_{\rm RDS}} = \begin{cases} 1.98 \pm 0.02, & \text{LO;} \\ 1.12 \pm 0.08, & \text{NLO.} \end{cases} \tag{2}$$

It follows from Eq.(**??**) that once next-to-leading order effects are accounted for, the application of RDS suppression cuts becomes much less important since a factor of two gain in luminosity gets reduced to $\mathcal{O}(10\%)$ gain.

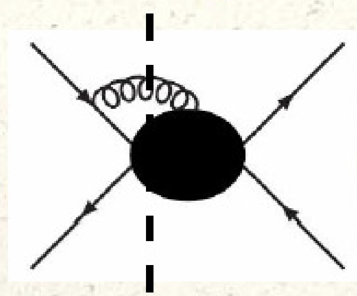
Asymmetries

- At leading order the asymmetry is generated by soft, non-collinear exchange between initial and final state

$$\sigma_{t\bar{t}j} \sim \frac{2C_F\alpha_s}{\pi}\ln^2\frac{m_t}{p_{\perp,j}}\,\sigma_{t\bar{t}}, \quad \sigma(y_t>0)-\sigma(y_t<0) \sim \frac{C_F\alpha_s}{\pi}\ln\frac{m_t}{p_{\perp,j}}\sigma_{t\bar{t}}$$

$$A_{\mathrm{FB}} = \frac{\sigma(y_t>0)-\sigma(y_t<0)}{\sigma_{t\bar{t}j}} \sim \left[\ln\frac{m_t}{p_{\perp,j}}\right]^{-1}$$

- At NLO, can generate asymmetry by hard exchanges and use soft initial-initial interference to provide regular double logarithmic enhancement of the cross-section



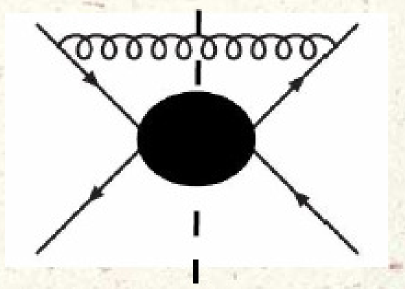


Diagram that shifts the asymmetry by +5 % at NLO