Top quark pair production and decay in association with a hard jet @ NLO QCD

Andreas Scharf

Julius-Maximilians-UNIVERSITÄT WÜRZBURG

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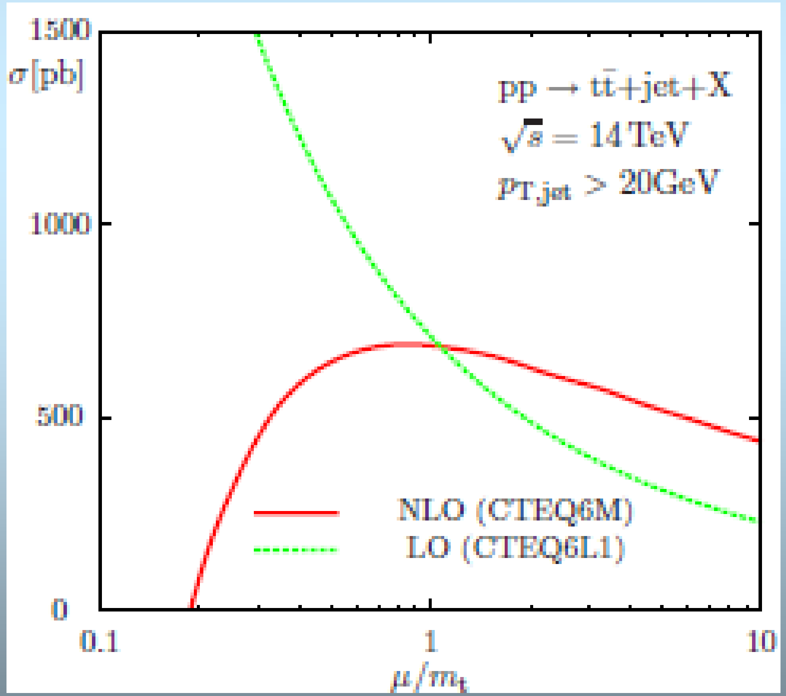
$t\bar{t}j$ production

- **LHC era in top quark physics**
  - **Associated $t\bar{t}$ production:** $t\bar{t}j,\ t\bar{t}\gamma,\ \ldots$
- **Large number of events**
  - **LHC @ 7 TeV (di-leptonic):** $\mathcal{O}(10^4)$ events for $\mathcal{L} = 10\ \mathrm{fb}^{-1}$
- **Complicated final states**
  - **Semi-leptonic: 5 jets, lepton + missing energy**

What is needed from theory ?

Accurate predictions

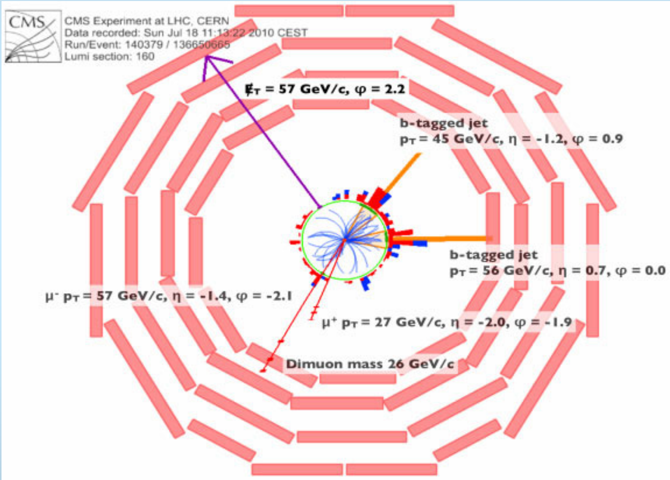
- NLO QCD corrections:
  - Reduce dependence on unphysical scales
  - Provide more realistic description of the final state



Dittmaier, Uwer, Weinzierl (2007)

Realistic setup

- Top quarks decay
  - Acceptance cuts are applied to decay products
  - Spin correlations are important for differential distributions



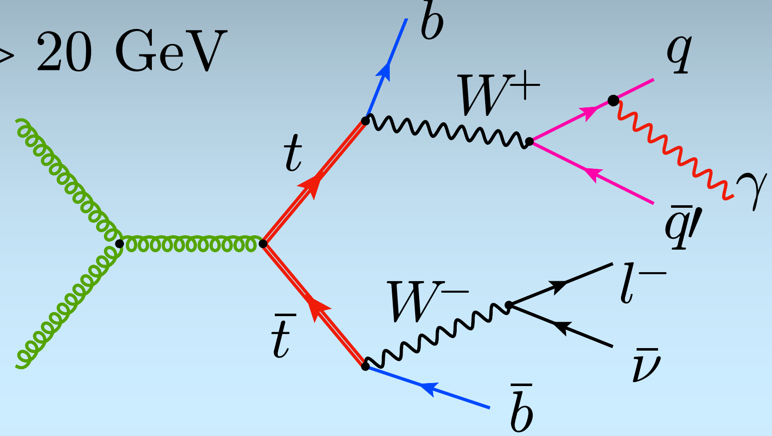
➔ **Description of top-quark/W decays required**

- NLO $t\bar{t}j$ production with LO top decays — Melnikov, Schulze (2010)
- NLO $t\bar{t}j$ production with parton shower — Alioli, Moch Uwer (2011); Kardos, Papadopoulos, Trocsanyi (2011)

Is that all ?

- Hard jet emission off top quark decay products ?
  - Example $t\bar{t}\gamma$ production: $p_T^\gamma > 20$ GeV

Photon radiation in decay yields 56 % to total cross section



- NLO corrections to (radiative) top-quark decays ?

Consistent treatment of top-quark and W-boson decays at NLO QCD

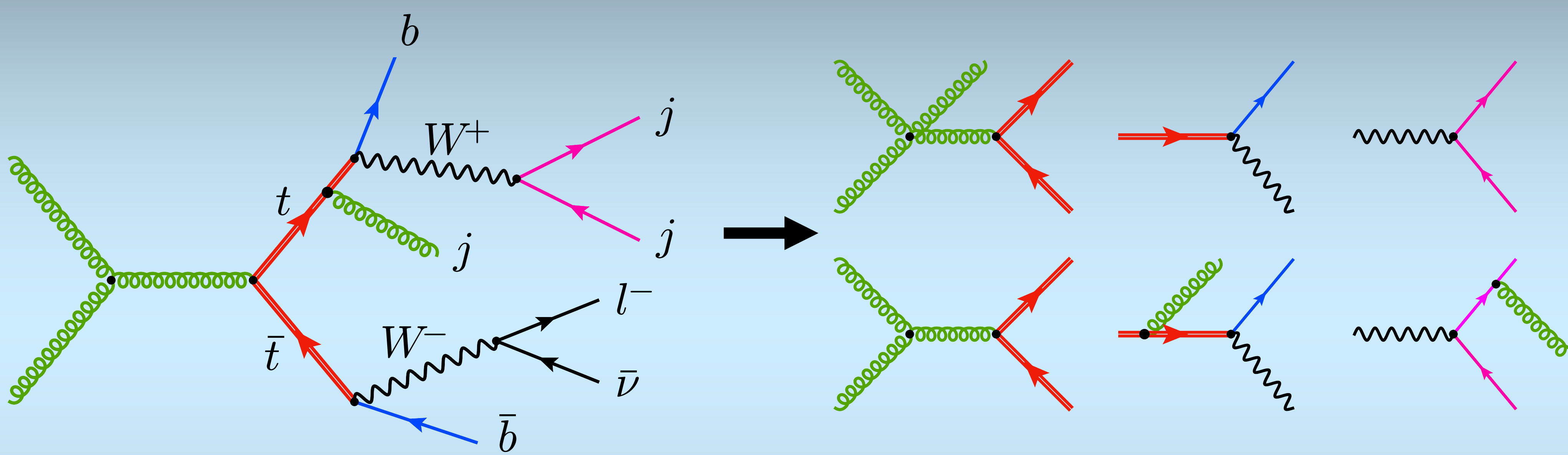
$$pp \to t\bar{t} + j \to b\bar{b}jj\ell^-\bar{\nu} + j$$

Full calculation | **Narrow width approximation** ✓

… is very complicated

LO $t\bar{t}j$ production

- **Narrow width approximation separates production from decay**



$$\left.\frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2}\right|_{\Gamma_t/m_t\to 0} = \frac{2\pi}{2m_t\Gamma_t}\,\delta(p_t^2-m_t^2)$$

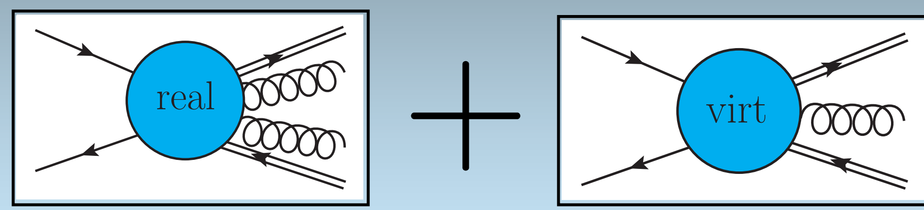
$$\frac{\Gamma_{\rm top}}{m_{\rm top}} \simeq 8\cdot 10^{-3} \ll 1$$

$$\frac{\Gamma_{\rm W}}{M_{\rm W}} \simeq 3\cdot 10^{-2} \ll 1$$

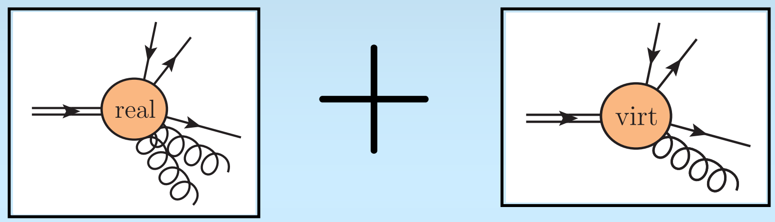
- **Two kinds of contributions @ LO**
  - **Hard jet emission in production:** $pp \to t\bar{t}+j \to b\bar{b}jj\ell^-\bar{\nu}+j$
  - **Hard jet emission in decay:** $pp \to t\bar{t} \to b\bar{b}jj\ell^-\bar{\nu}+j$

NLO $t\bar{t}j$ production

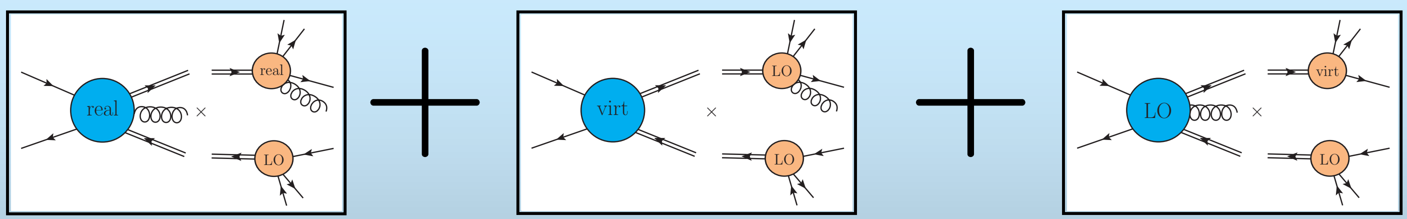
- Three kinds of contributions
  - Production



  - Decay



  - Mixed



- Neglect non-resonant and non-factorizable corrections

Small contributions !!!

Melnikov, Yakovlev (1996)
Beenakker, Berends, Chapovsky (1999)

Explicit calculations for $t\bar{t}$:

0.8 % for σ_{tot}

Denner, Dittmaier, Kallweit, Pozzorini (2010)
Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek (2010)

Cross-sections & K-factors

- **Tevatron (semi-leptonic):**

Only 60 % of the events originate from jet emission in production

$$\sigma_{\rm LO} = 46.3({\rm Prod}) + 29({\rm Dec}) = 75.3 \text{ fb}$$

$$\sigma_{\rm NLO} = 47.7({\rm Prod}) + 36.7({\rm Dec}) - 5.5({\rm Mix}) = 78.9 \text{ fb}$$

K-factor (NLO): 1.05

K-factor (NLO production only): 1.03

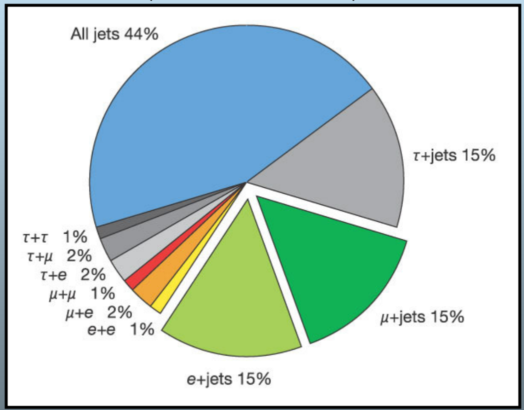
} **K-factor remains unchanged accidentally !**

- **Branching ratios and the extraction of the total cross-section**

$t\bar{t}$ **production:** $\sigma^{\rm Total}_{t\bar{t}} = \sigma^{\rm measure}_{b\bar{b}\ell\nu jj} \times \mathcal{B}(\bar{t} \to \bar{b}jj)^{-1} \times \mathcal{B}(t \to b\ell\nu)^{-1}$

For $t\bar{t}j$ this is not longer valid

$$\sigma^{\rm Total}_{t\bar{t}j} \neq \sigma^{\rm measure}_{b\bar{b}\ell\nu jjj} \times \mathcal{B}(\bar{t} \to \bar{b}jj)^{-1} \times \mathcal{B}(t \to b\ell\nu)^{-1}$$



Cross-sections & K-factors

- LHC @ 7 TeV (di-leptonic):

$$\sigma_{\mathrm{LO}} = 316.9(\mathrm{Prod}) + 33.4(\mathrm{Dec}) = 350.3\ \mathrm{fb}$$

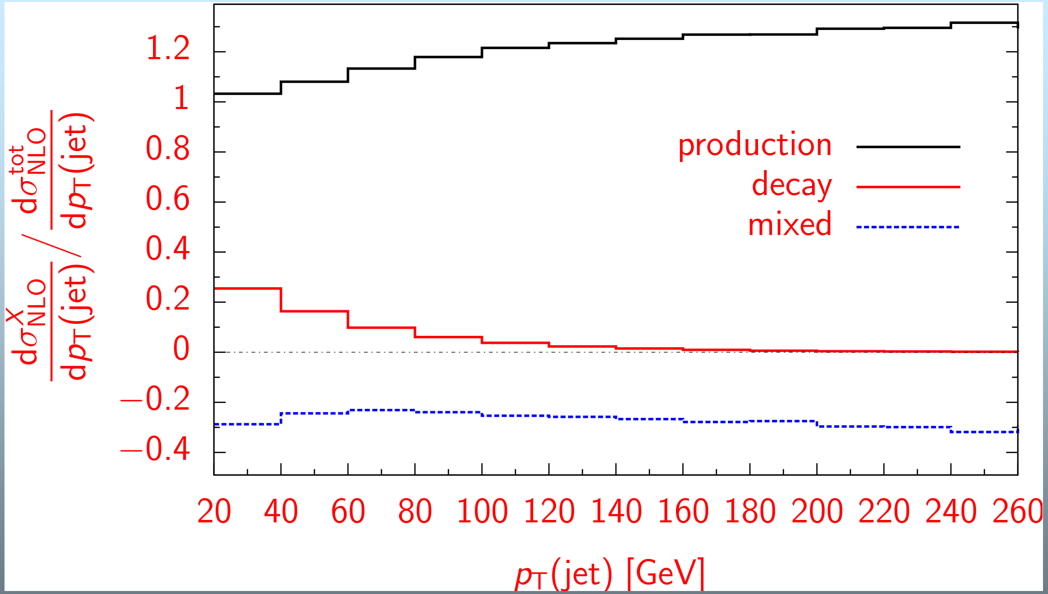
$$\sigma_{\mathrm{NLO}} = 323(\mathrm{Prod}) + 40.5(\mathrm{Dec}) - 75.5(\mathrm{Mix}) = 288\ \mathrm{fb}$$

Mixed contributions lower the cross-section significantly

K-factor (NLO): 0.82

K-factor (NLO production only): 1.02

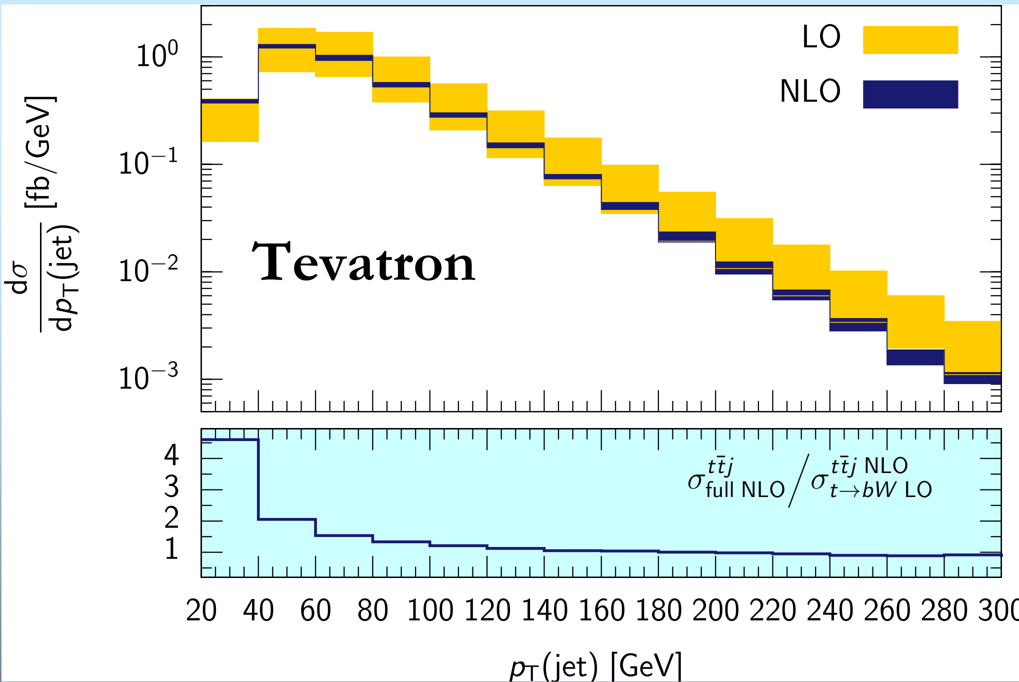
→ **K-factor changes about 20 %**



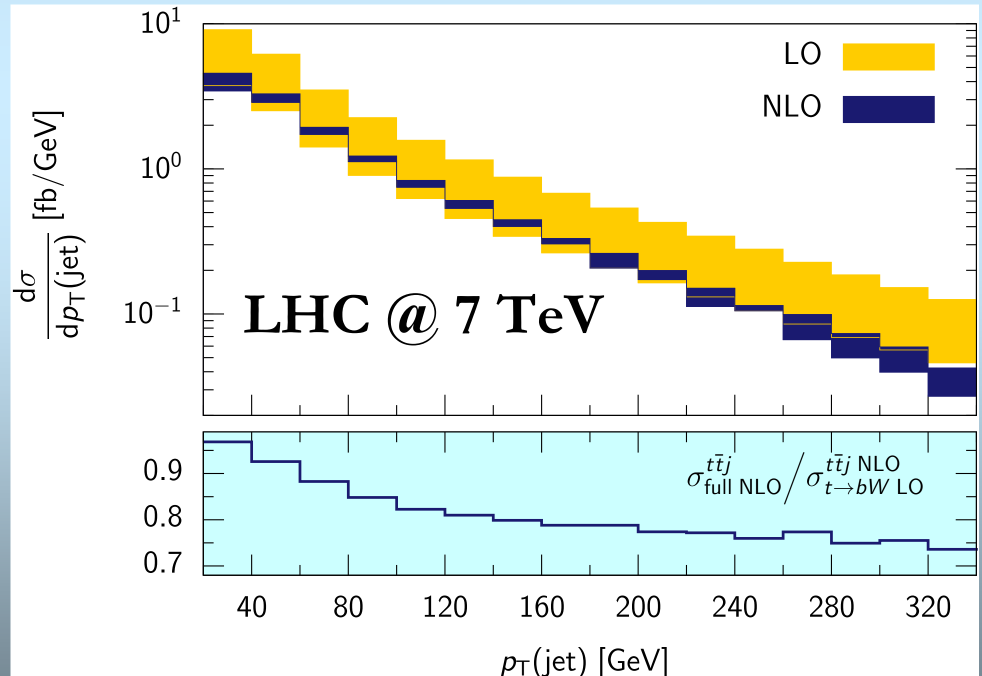
Differential distributions

- Significant reduction of scale-dependence $m_t/2 < \mu < 2m_t$
- Lower panel shows ratio of NLO over NLO-production only
  - Large effects from radiative decays and non-uniform shape changes

Hardest jet p_T



Hardest jet p_T



Summary & Conclusion

- **NLO corrections to** $t\bar{t}j$

  Including (radiative) top quark decays consistently at NLO QCD

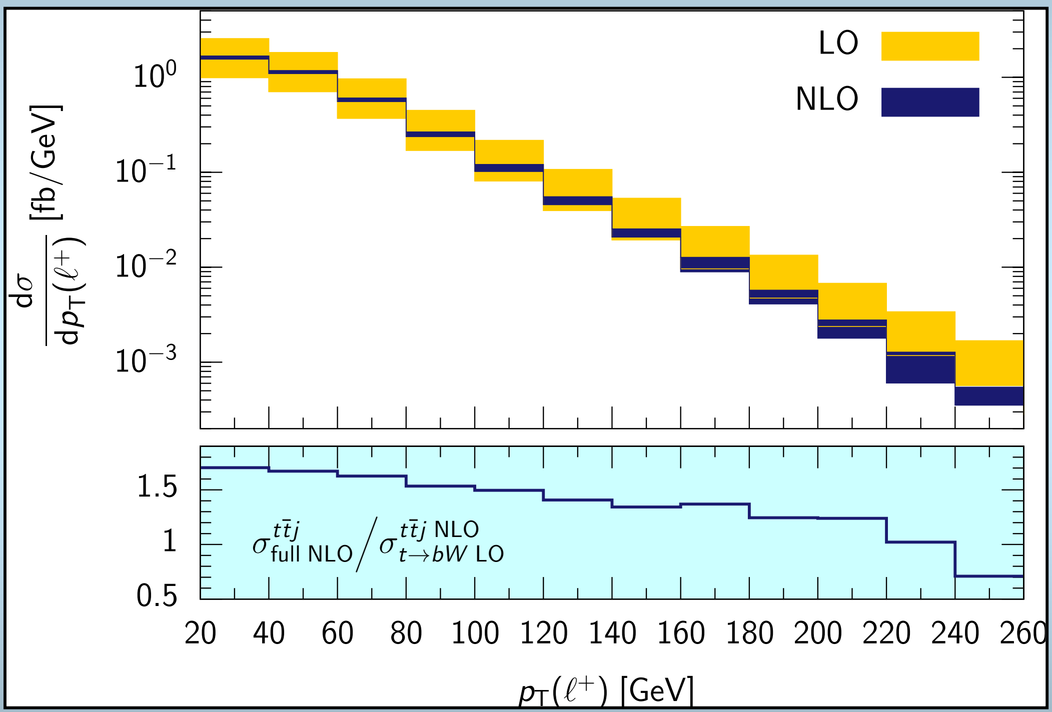
- **Realistic and flexible setup**

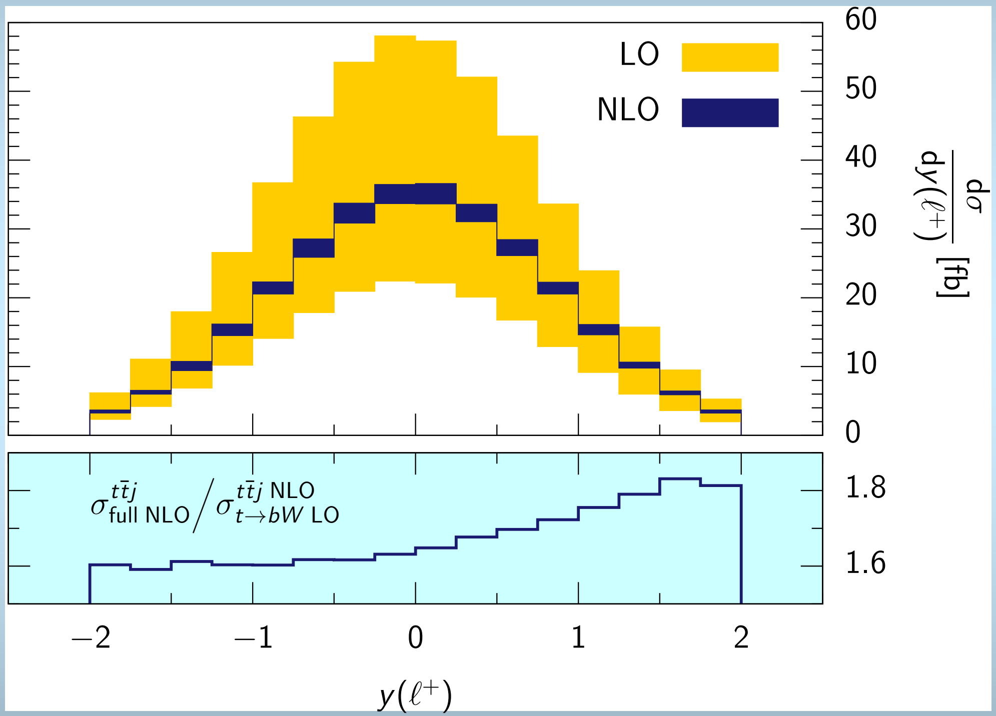
- **Jet radiation off decay products is not negligible**
  - ➔ **New "mixed" contributions appearing @ NLO**
  - ➔ **Sizeable contributions and significant shape changes**

- **Similar implications for other processes ?**

Differential Distributions

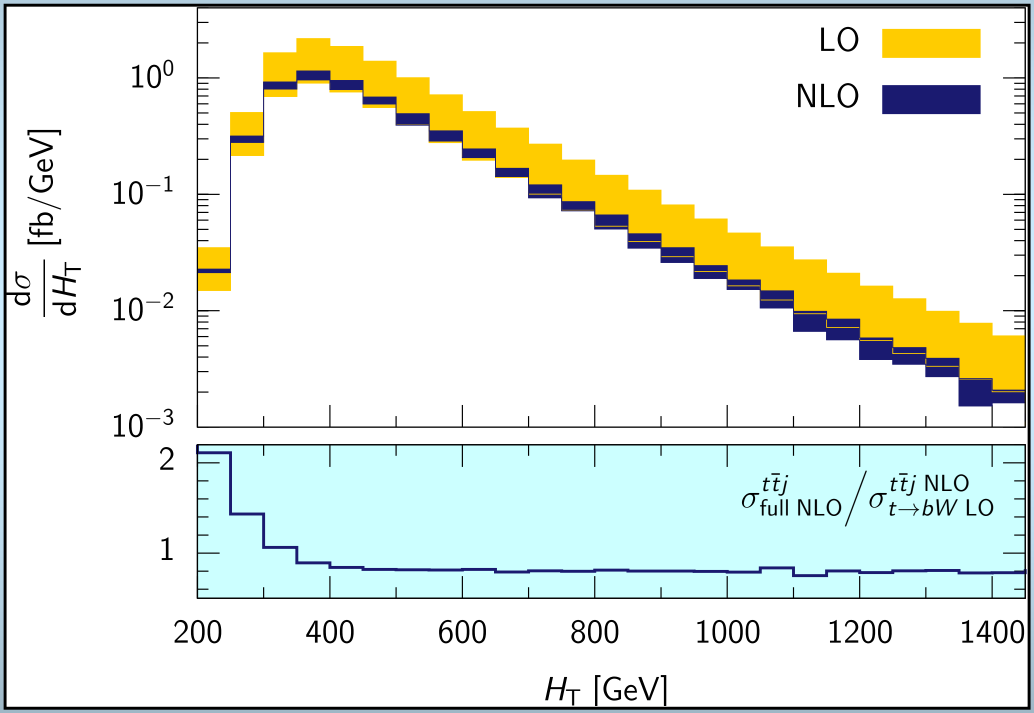
- Tevatron

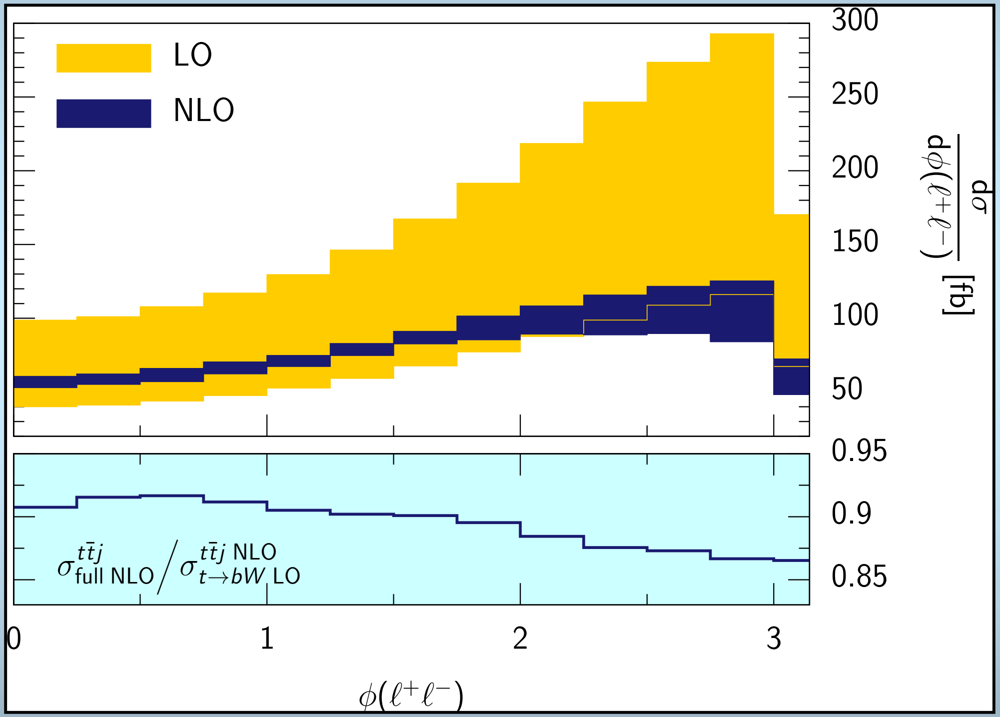




Differential Distributions

❑ LHC @ 7 TeV

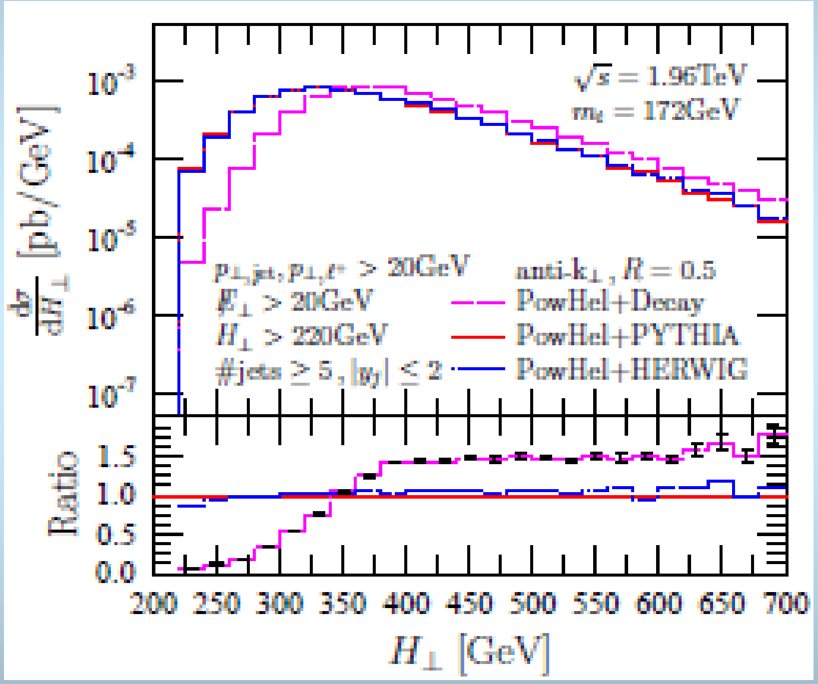


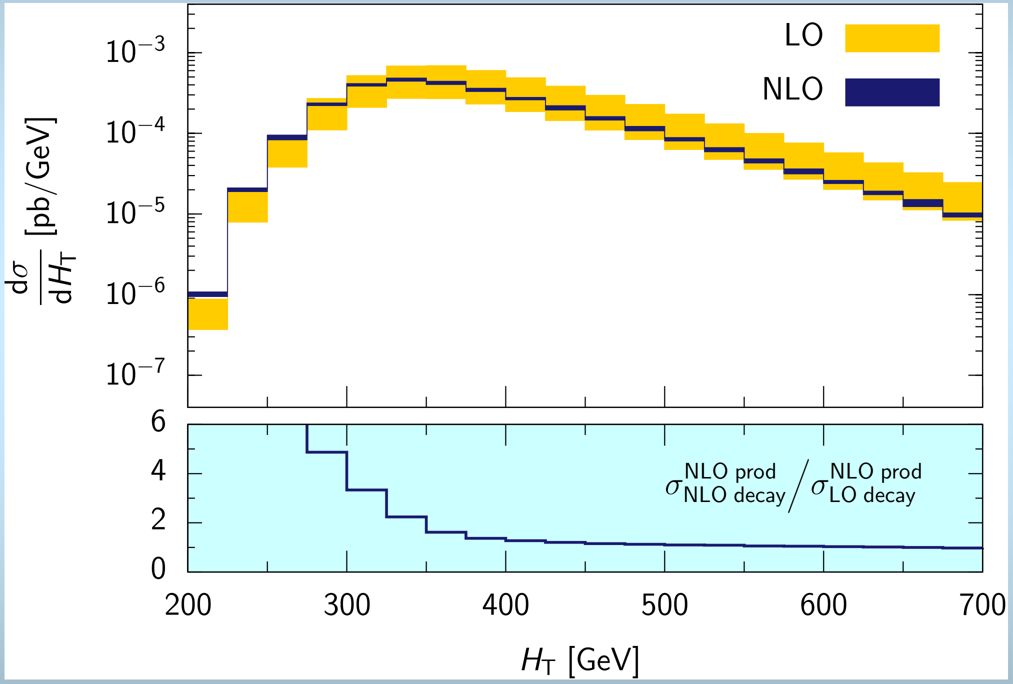


NLO vs. parton shower

- Similar shape change from parton shower

Kardos, Papadopoulos, Trocsanyi (2011)





Acceptance cuts used

- **Tevatron:** **kT jet algorithm:** $\Delta R(j,j) > 0.5$

$p_T^{\ell} > 20$ GeV $\quad |y_\ell| < 2$

$E_T^{\rm miss} > 20$ GeV $\quad |y_j| < 2 \quad$ 2 b-tags required

$p_T^{j} > 20$ GeV $\quad \#j \geq 5$

$H_T = E_T^{\rm miss} + \sum_i E_T^i > 220$ GeV

- **LHC:** **anti-kT jet algorithm:** $\Delta R(j,j) > 0.4$

$p_T^{\ell} > 25$ GeV $\quad |y_\ell| < 2.5$

$E_T^{\rm miss} > 50$ GeV $\quad |y_j| < 2.5 \quad$ 2 b-tags required

$p_T^{j} > 25$ GeV $\quad \#j \geq 3$

$H_T = E_T^{\rm miss} + \sum_i E_T^i > 220$ GeV