LoopFest *XI*

$t\bar{t} + \text{jet}$ production:

QCD corrections in production and decay

Markus Schulze

Argonne
NATIONAL LABORATORY

$t\bar{t} + \text{jet(s)}$

$t\bar{t} + \gamma$

$t\bar{t} + Z$

$t\bar{t} + H$

$t\bar{t} + W$

$t\bar{t}$ + jet(s)

$t\bar{t}$ + V

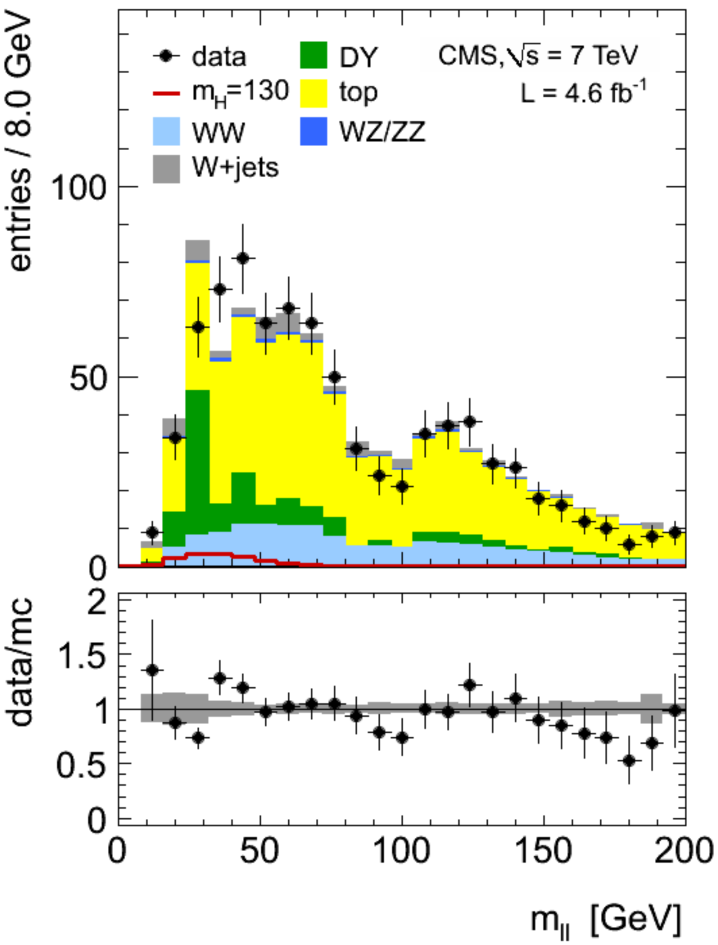
The study of
associated top quark pair production
marks the post-Tevatron era in top quark physics

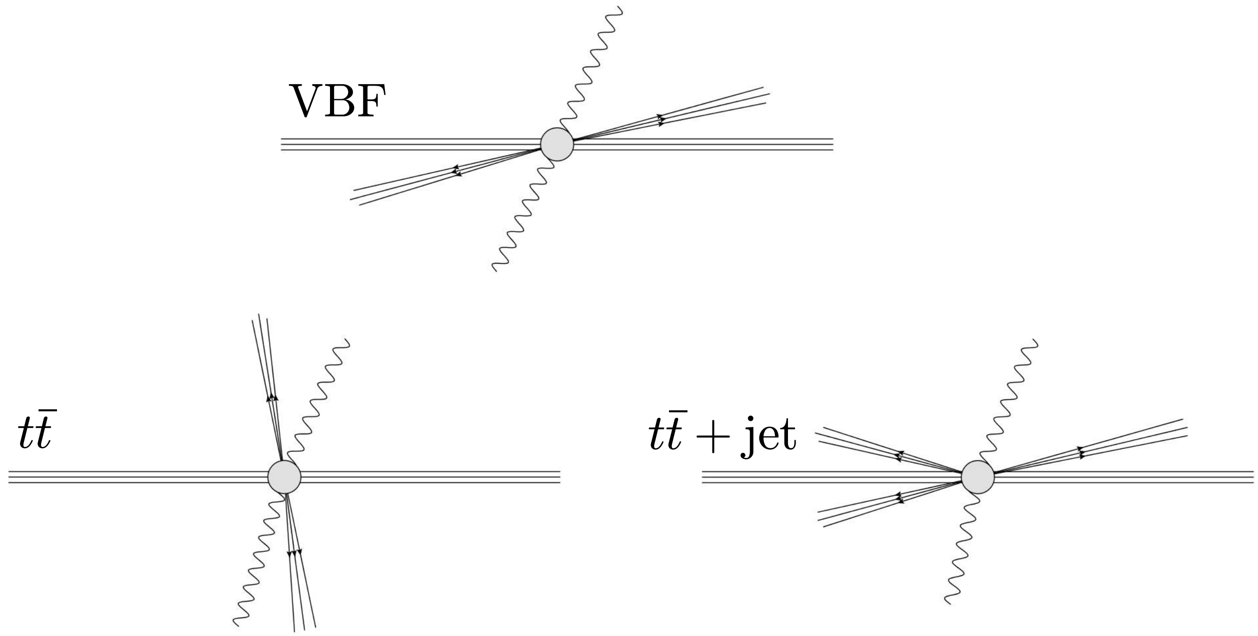
$t\bar{t}$ + H

$t\bar{t}$ + W

Motivation

I. Background to Higgs search in VBF





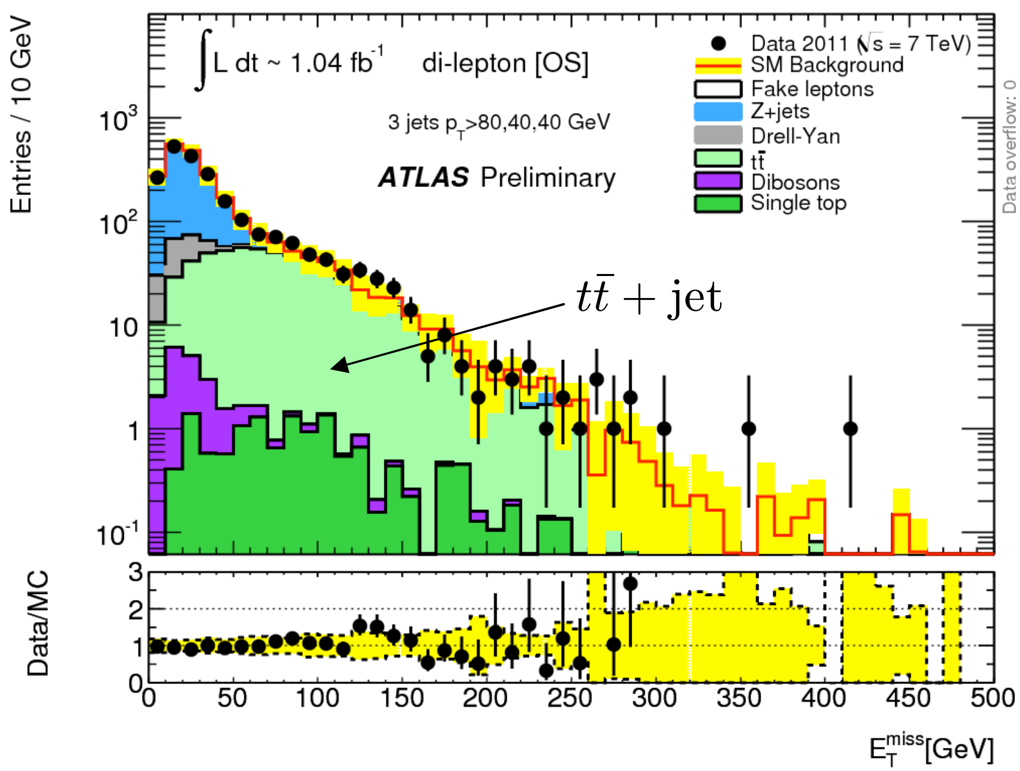
$$t\bar{t}\ :\ 1\%$$
$$t\bar{t} + \text{jet}\ :\ 80\% \qquad \text{of all backgrounds}$$
$$t\bar{t} + 2\text{jet}\ :\ 9\%$$

Motivation

II. Background to many New Physics searches

$$\tilde{g}\tilde{q} \to \tilde{q}qq\tilde{\chi}_2^0 \to qqq\chi_1^-\mu^+\tilde{\chi}_1^0 \to qqqe^-\tilde{\chi}_1^0\mu^+\tilde{\chi}_1^0$$

2 OS leptons + 3jets + MET

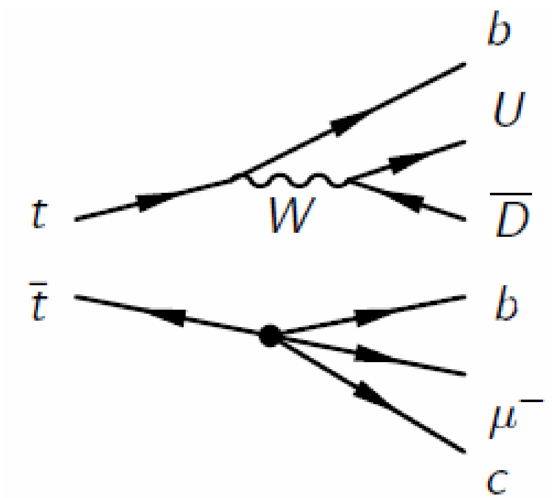


Motivation

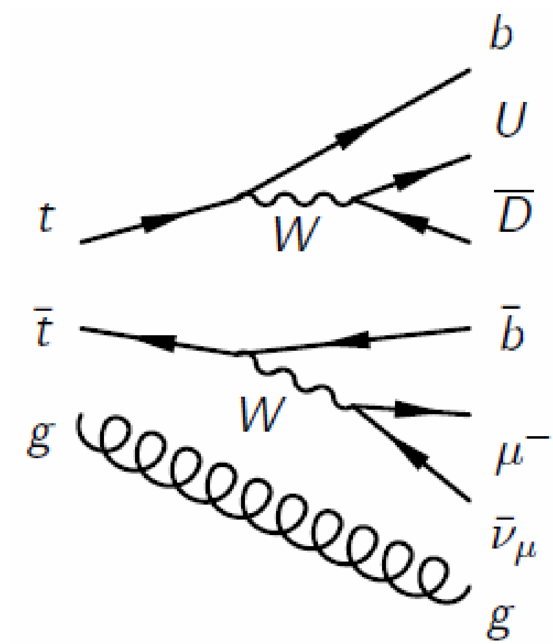
II. Background to many New Physics searches

Baryon number violating top couplings

[Dong,Durieux,Han,Gerad,Maltoni]



signal



background

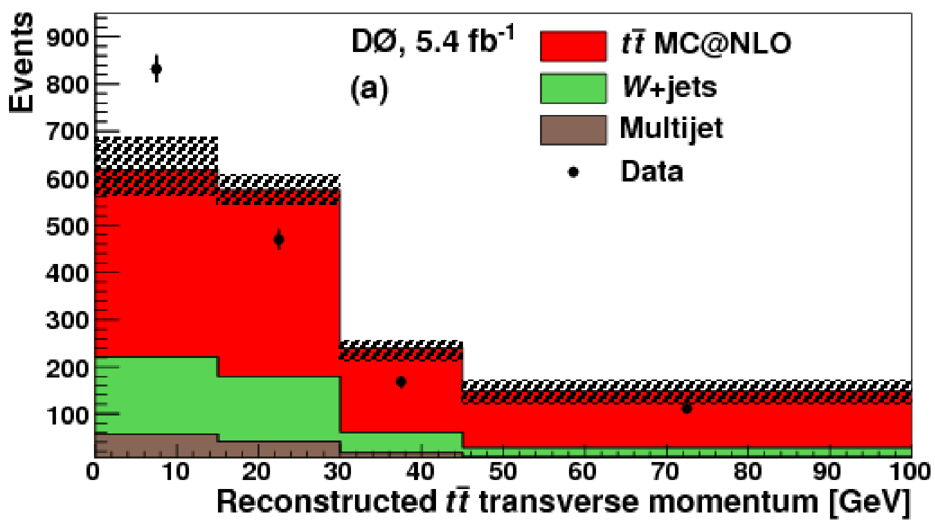
signal and background differ only by missing energy

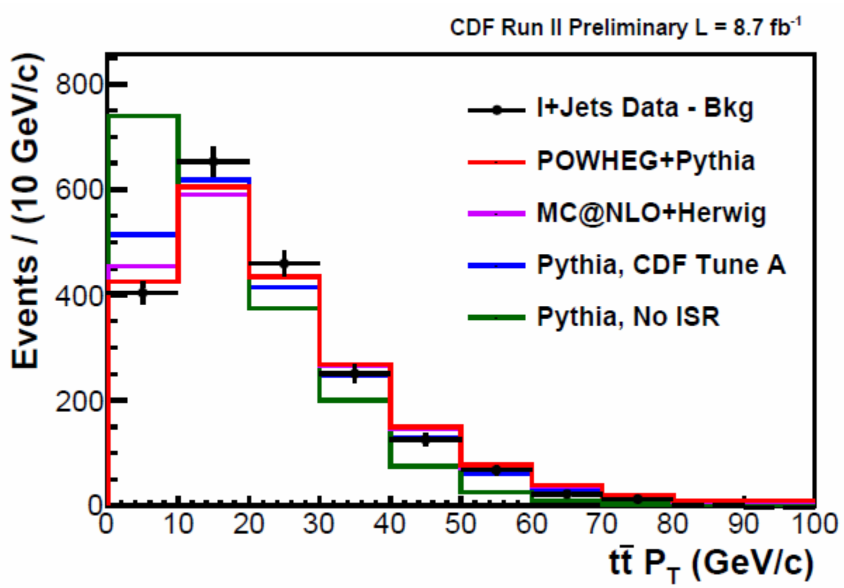
Motivation

III. Standard Candle

Transverse momentum of the ttbar pair

DZero and CDF (prelim.)



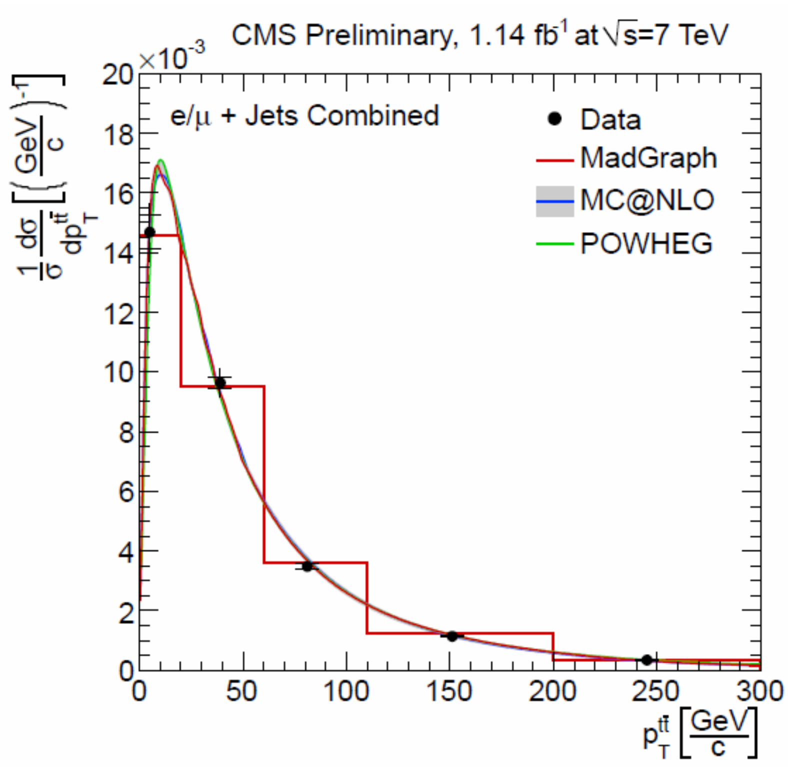


Motivation

III. Standard Candle

Measurement of top quark differential cross sections

CMS, February 2012

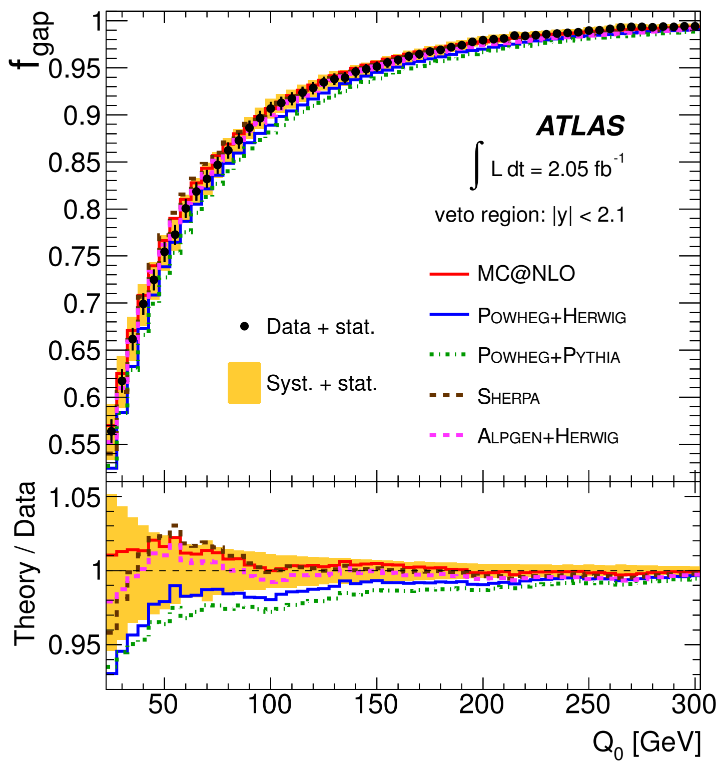


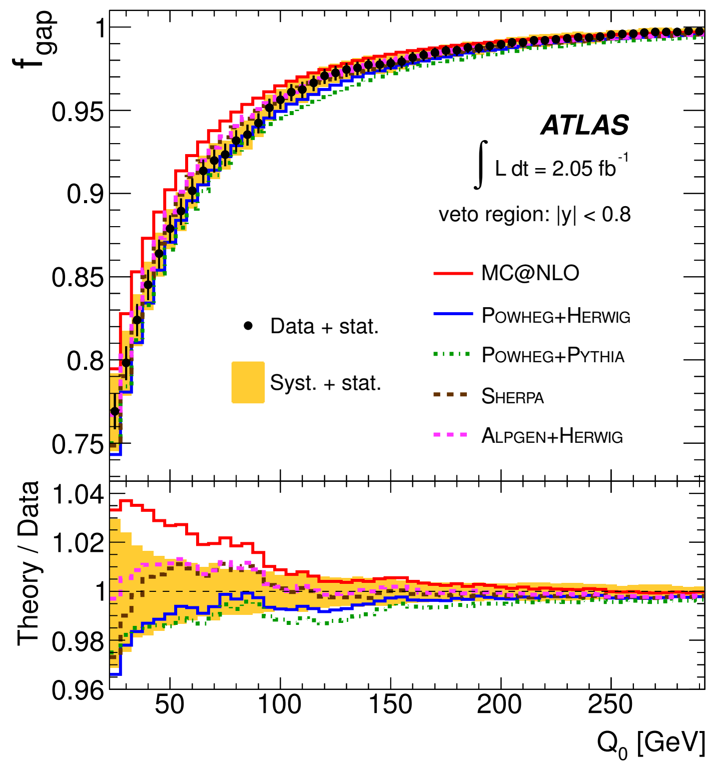
Motivation

III. Standard Candle

Measurement of ttbar production with a veto on additional central jet activity

ATLAS, March 2012





Predictions at NLO QCD

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

Stable top quarks:

2007 [Dittmaier,Uwer,Weinzierl]
2010 [Bevilacqua,Czakon,Papadopoulos,Worek]

Top quark decays

at LO QCD: 2010 [Melnikov,M.S]
at NLO QCD: 2012 [Melnikov,Scharf,M.S]

Parton showered:

2011 [Kardos,Papadopolous,Trocsanyi]
2011 [Alioli,Moch,Uwer]

NLO QCD corrections to top quark pair production in association with one hard jet at hadron colliders

K.Melnikov, M.S. Nucl.Phys.B840 (2010)

Top quark pair production in association with a jet: QCD corrections and jet radiation in top quark decays

K.Melnikov, A. Scharf, M.S. Phys.Rev.D85 (2012)

Framework

$$pp \to t\bar{t} + \text{jet} \to b\bar{b}\,\ell^-\ell^+\,\bar{\nu}\nu + \text{jet}$$

at NLO QCD

Features:

- **decays of top quarks:**
  realistic final state, acceptances
- **spin correlations:**
  kinematic distributions
- **radiative top quark decays:**
  changes normalization and shapes
- **NLO corrections in production & decay:**
  reduced scale uncertainty,
  models soft / collinear and
  large angle emission exact to $\mathcal{O}(\alpha_s)$

Approximations:

- **largely off-shell top quarks, W's**:
  neglect non-resonant corrections
  $\Rightarrow$ *apply narrow-width approximation*
  valid up to $\mathcal{O}(\Gamma_t/m_t)$
- **neglect shower effects** and
  higher order threshold corrections

Production process

- Virtual corrections: Generalized D-dimensional unitarity + OPP

  [Ellis,Giele,Kunszt,Melnikov]

  [Ossola,Papadopoulus,Pittau]

- Real corrections: Berends-Giele recursion relations,
  Dipole subtraction with α-cutoff parameters

  [Catani,Dittmaier,Seymour,Trocsanyi]

Production process

- Virtual corrections: Generalized D-dimensional unitarity + OPP

[Ellis,Giele,Kunszt,Melnikov]

[Ossola,Papadopoulus,Pittau]

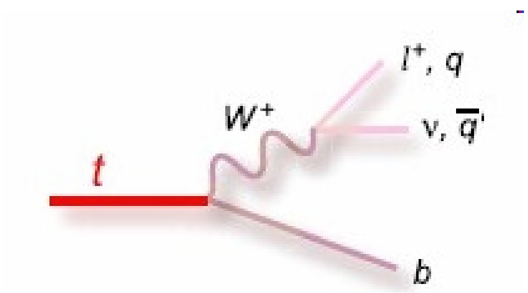
- Real corrections: Berends-Giele recursion relations,
  Dipole subtraction with α-cutoff parameter

[Catani,Dittmaier,Seymour,Trocsanyi]

- Partonic processes:

$qg \to \bar{t}t\ q$	$gg \to \bar{t}t\ g\ g$	$\bar{q}q \to \bar{t}t\ (\bar{q}q + \bar{q}'q')$	$qg \to \bar{t}t\ q\ g_{\text{decay}}$
$\bar{q}g \to \bar{t}t\ \bar{q}$	$\bar{q}q \to \bar{t}t\ g\ g$	$q\bar{q}' \to \bar{t}t\ q\bar{q}'$	$\bar{q}g \to \bar{t}t\ \bar{q}\ g_{\text{decay}}$
$gg \to \bar{t}t\ g$	$gg \to \bar{t}t\ q\bar{q}$	$qq' \to \bar{t}t\ qq'$	$gg \to \bar{t}t\ g\ g_{\text{decay}}$
$\bar{q}q \to \bar{t}t\ g$	$qg \to \bar{t}t\ q\ g$	$\bar{q}\bar{q}' \to \bar{t}t\ \bar{q}\bar{q}'$	$\bar{q}q \to \bar{t}t\ g\ g_{\text{decay}}$
$gg \to \bar{t}t\ \ g_{\text{decay}}$	$\bar{q}g \to \bar{t}t\ \bar{q}\ g$	$qq \to \bar{t}t\ qq$	$gg \to \bar{t}t\ \ g_{\text{decay}}\ g_{\text{decay}}$
$\bar{q}q \to \bar{t}t\ \ g_{\text{decay}}$		$\bar{q}\bar{q} \to \bar{t}t\ \bar{q}\bar{q}$	$\bar{q}q \to \bar{t}t\ \ g_{\text{decay}}\ g_{\text{decay}}$
			$gg \to \bar{t}t\ \ q_{\text{decay}}\ \bar{q}_{\text{decay}}$
			$\bar{q}q \to \bar{t}t\ \ q_{\text{decay}}\ \bar{q}_{\text{decay}}$

Top quark decays



Basic idea:

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

$$|\mathcal{M}|^2 = |\bar{\tilde{u}}(p_t)\,\tilde{\mathcal{M}}(gg \to \bar{t}tg)\,\tilde{v}(p_{\bar{t}})|^2 \quad + \mathcal{O}(\tfrac{\Gamma_t}{m_t})$$

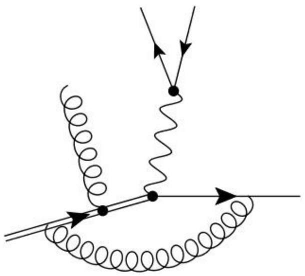
- retains all spin correlations
- allows straightforward implementation of NLO corrections

Quality of narrow-width approximation:

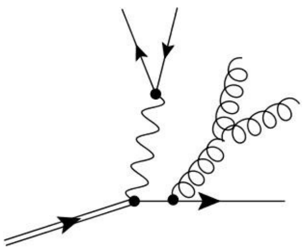
- formal suppression $\sim \mathcal{O}(\Gamma_t/m_t)$ requires full $\int \mathrm{d}m_t \ldots$ acceptance cuts constrain this integration but not too violently
- dedicated study of off-shell effects in $t\bar{t} \to W^+W^-b\bar{b}$ show $O(1\%)$ effects; in some corners of phase space 10-20%

[Denner,Dittmaier,Kallweit,Pozzorini,Schulze]

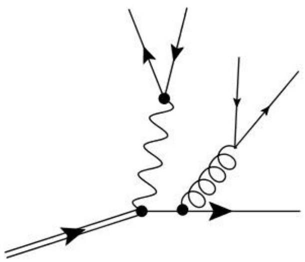
Top quark decays



Virtual corrections:
traditional techniques (P-V integral reduction)



Real corrections:
need to derive new subtraction terms,
decay kinematics (1→n) cannot be handled with
standard Catani *et al.* dipoles



final-final: borrow from Catani *et al.*

initial-final: only soft singularity → absorb into *f-i* dipole

final-initial: **NEW**, following construction of
[Ellis,Campbell,Tramontano] (single top)

⇒ complete set of dipoles for any decay process
(including *alpha* cut-off parameter)

Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

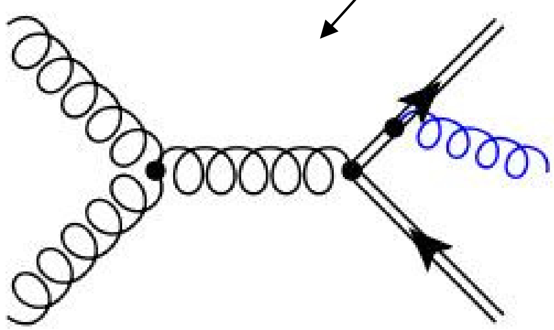
$$\sigma \stackrel{\text{LO}}{=} \sigma_{t\bar{t}+\text{jet}}\,\mathcal{B}_{t\bar{t}} \;+\; \sigma_{t\bar{t}}\,\mathcal{B}_{t\bar{t}+\text{jet}}$$

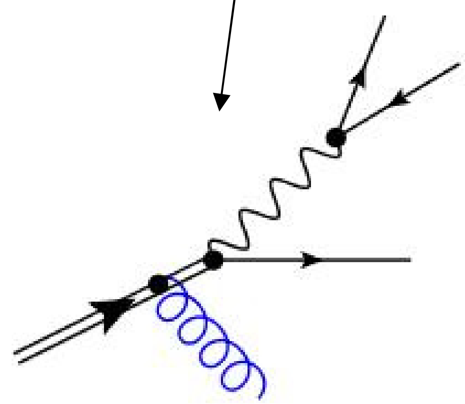
Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

$$\sigma \stackrel{\text{LO}}{=} \sigma_{t\bar{t}+\text{jet}}\,\mathcal{B}_{t\bar{t}} + \sigma_{t\bar{t}}\,\mathcal{B}_{t\bar{t}+\text{jet}}$$





$$\mathcal{B}_{t\bar{t}+\text{jet}} = \mathcal{B}_{t+\text{jet}}\,\mathcal{B}_{\bar{t}} + \mathcal{B}_{t}\,\mathcal{B}_{\bar{t}+\text{jet}}$$

Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

$$\sigma^{\mathrm{NLO}} = \sigma_{t\bar{t}+\mathrm{jet}}\,\mathcal{B}_{t\bar{t}} + \sigma_{t\bar{t}}\,\mathcal{B}_{t\bar{t}+\mathrm{jet}}$$

$$+\,\sigma_{t\bar{t}+2\mathrm{jet}}\,\mathcal{B}_{t\bar{t}} + \sigma_{t\bar{t}}\,\mathcal{B}_{t\bar{t}+2\mathrm{jet}} + \sigma_{t\bar{t}+\mathrm{jet}}\,\mathcal{B}_{t\bar{t}+\mathrm{jet}}$$

Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}} + \sigma^{\mathrm{LO}}_{t\bar{t}}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}+1j} + \left(\sigma^{\mathrm{virt}}_{t\bar{t}+1j} + \sigma^{\mathrm{real}}_{t\bar{t}+2j}\right)\mathcal{B}^{\mathrm{LO}}_{t\bar{t}}$$

$$+ \sigma^{\mathrm{LO}}_{t\bar{t}}\left(\mathcal{B}^{\mathrm{virt}}_{t\bar{t}+1j} + \mathcal{B}^{\mathrm{real}}_{t\bar{t}+2j}\right) + \sigma^{\mathrm{real}}_{t\bar{t}+1j}\mathcal{B}^{\mathrm{real}}_{t\bar{t}+1j} + \sigma^{\mathrm{virt}}_{t\bar{t}}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}+1j} + \sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathcal{B}^{\mathrm{virt}}_{t\bar{t}}$$

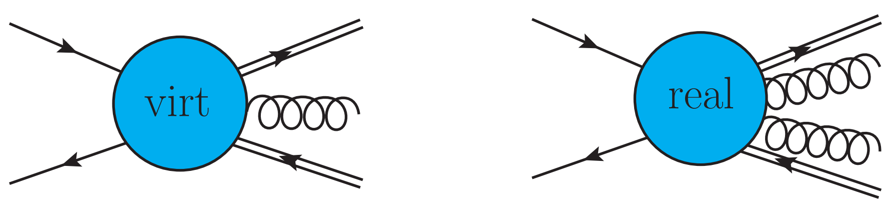
Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

$$\sigma \overset{\text{NLO}}{=} \sigma^{\text{LO}}_{t\bar{t}+1j}\mathcal{B}^{\text{LO}}_{t\bar{t}} + \sigma^{\text{LO}}_{t\bar{t}}\mathcal{B}^{\text{LO}}_{t\bar{t}+1j} + \left(\sigma^{\text{virt}}_{t\bar{t}+1j} + \sigma^{\text{real}}_{t\bar{t}+2j}\right)\mathcal{B}^{\text{LO}}_{t\bar{t}}$$

$$+ \sigma^{\text{LO}}_{t\bar{t}}\left(\mathcal{B}^{\text{virt}}_{t\bar{t}+1j} + \mathcal{B}^{\text{real}}_{t\bar{t}+2j}\right) + \sigma^{\text{real}}_{t\bar{t}+1j}\mathcal{B}^{\text{real}}_{t\bar{t}+1j} + \sigma^{\text{virt}}_{t\bar{t}}\mathcal{B}^{\text{LO}}_{t\bar{t}+1j} + \sigma^{\text{LO}}_{t\bar{t}+1j}\mathcal{B}^{\text{virt}}_{t\bar{t}}$$



„production“

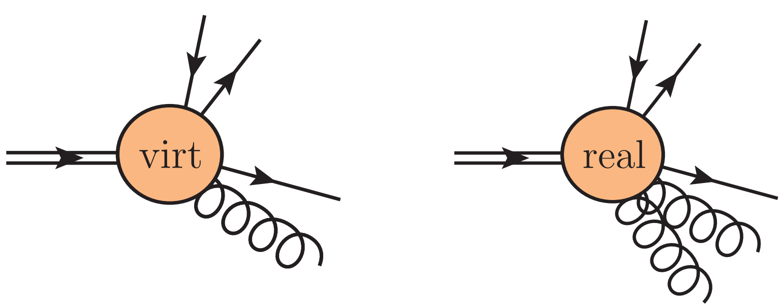
Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}} + \sigma^{\mathrm{LO}}_{t\bar{t}}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}+1j} + \left(\sigma^{\mathrm{virt}}_{t\bar{t}+1j} + \sigma^{\mathrm{real}}_{t\bar{t}+2j}\right)\mathcal{B}^{\mathrm{LO}}_{t\bar{t}}$$

$$+ \sigma^{\mathrm{LO}}_{t\bar{t}}\left(\mathcal{B}^{\mathrm{virt}}_{t\bar{t}+1j} + \mathcal{B}^{\mathrm{real}}_{t\bar{t}+2j}\right) + \sigma^{\mathrm{real}}_{t\bar{t}+1j}\mathcal{B}^{\mathrm{real}}_{t\bar{t}+1j} + \sigma^{\mathrm{virt}}_{t\bar{t}}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}+1j} + \sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathcal{B}^{\mathrm{virt}}_{t\bar{t}}$$



„decay“

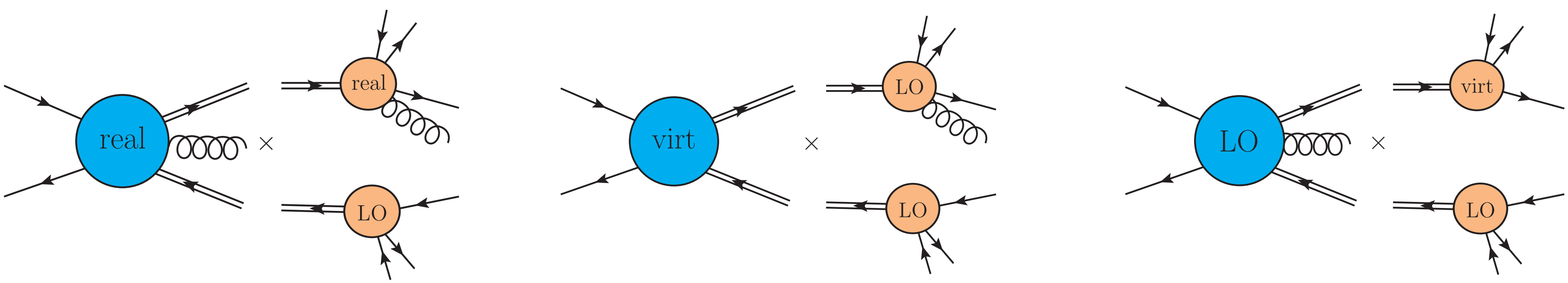
Combining production and decay

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay as well as jet radiation in production and in decay

$$\sigma \overset{\text{NLO}}{=} \sigma^{\text{LO}}_{t\bar{t}+1j}\mathcal{B}^{\text{LO}}_{t\bar{t}} + \sigma^{\text{LO}}_{t\bar{t}}\mathcal{B}^{\text{LO}}_{t\bar{t}+1j} + \left(\sigma^{\text{virt}}_{t\bar{t}+1j} + \sigma^{\text{real}}_{t\bar{t}+2j}\right)\mathcal{B}^{\text{LO}}_{t\bar{t}}$$

$$+ \sigma^{\text{LO}}_{t\bar{t}}\left(\mathcal{B}^{\text{virt}}_{t\bar{t}+1j} + \mathcal{B}^{\text{real}}_{t\bar{t}+2j}\right) + \sigma^{\text{real}}_{t\bar{t}+1j}\mathcal{B}^{\text{real}}_{t\bar{t}+1j} + \sigma^{\text{virt}}_{t\bar{t}}\mathcal{B}^{\text{LO}}_{t\bar{t}+1j} + \sigma^{\text{LO}}_{t\bar{t}+1j}\mathcal{B}^{\text{virt}}_{t\bar{t}}$$



„mixed“

Phenomenology

LHC 7 TeV

$$pp \to t\bar{t} + \text{jet} \to b\bar{b}\ \ell^-\ell^+\ \bar{\nu}\nu + \text{jet}$$

$$p_\mathrm{T}^\mathrm{jet} > 25\ \mathrm{GeV} \qquad |y^\mathrm{jet}| < 2.5$$

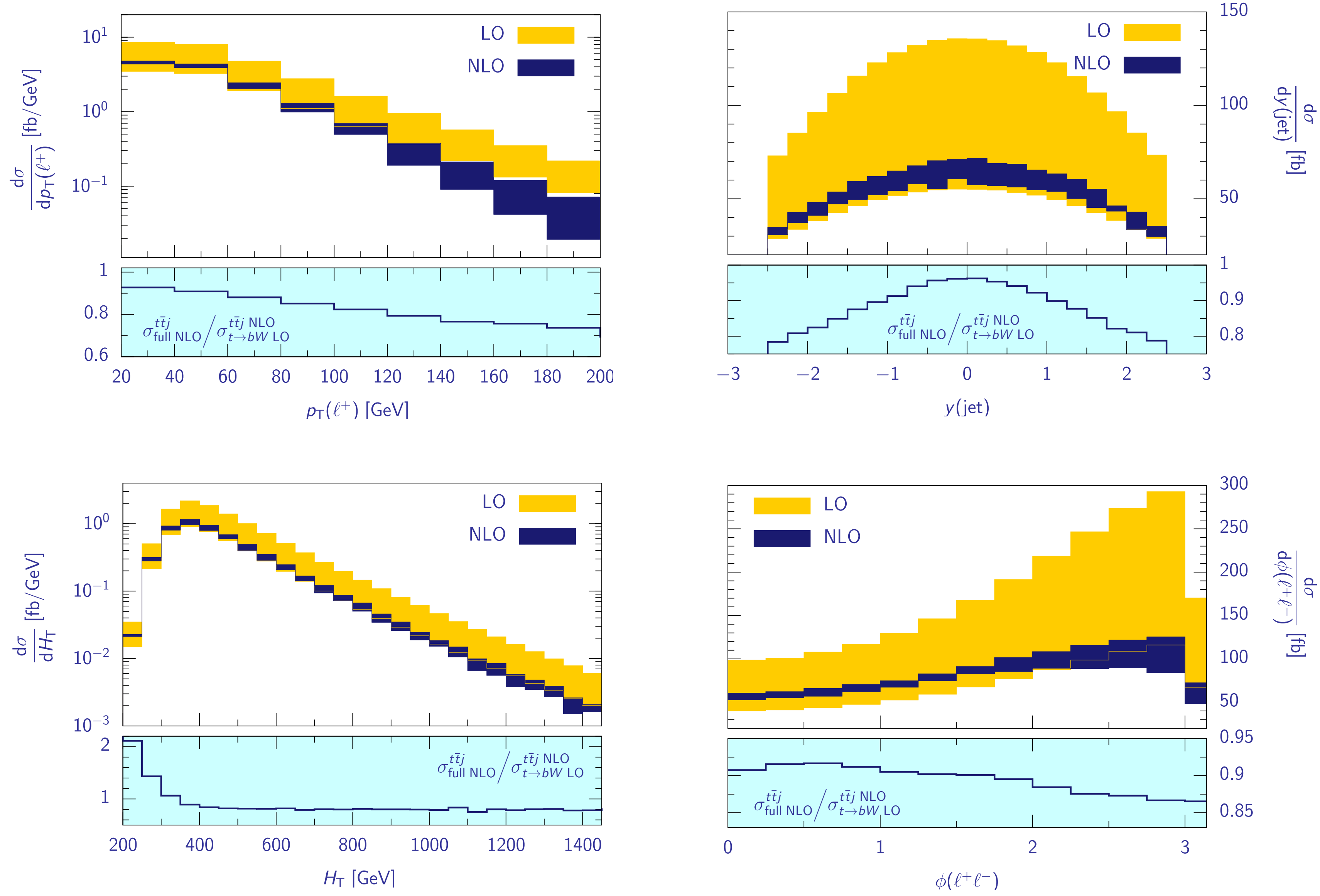
$$p_\mathrm{T}^\ell > 25\ \mathrm{GeV} \qquad |y^\ell| < 2.5$$

$$p_\mathrm{T}^\mathrm{miss} > 50\ \mathrm{GeV} \qquad \Delta R(j,j) > 0.4$$

$$\mu_\mathrm{R} = \mu_\mathrm{F} = m_t$$

$$m_t = 172\ \mathrm{GeV}$$

Phenomenology

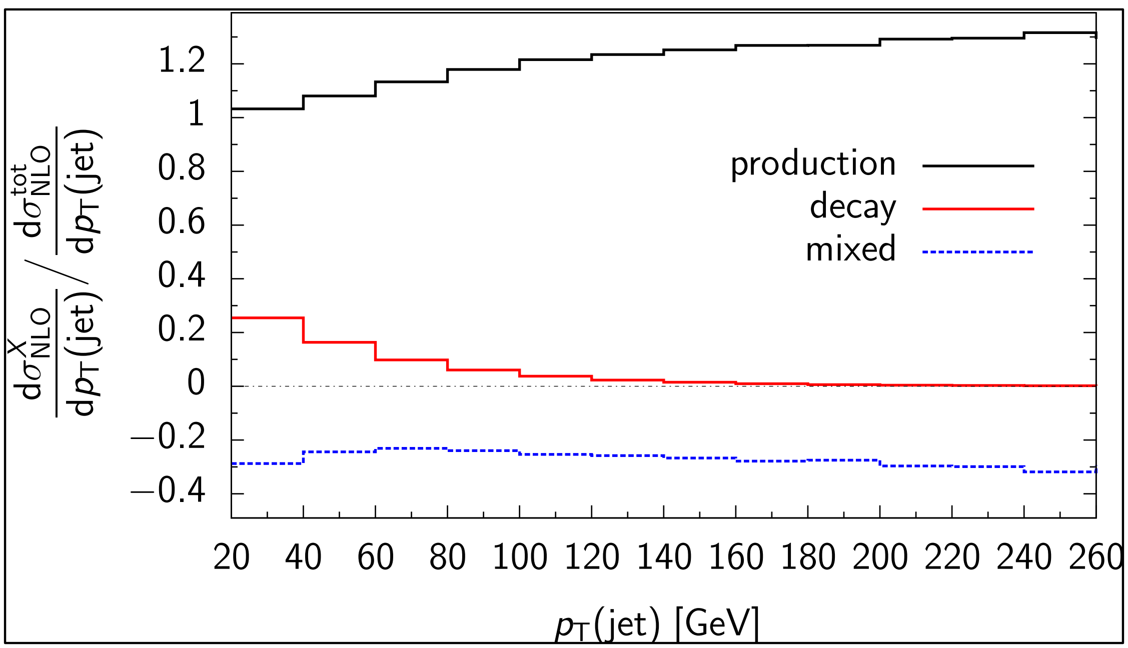


Phenomenology

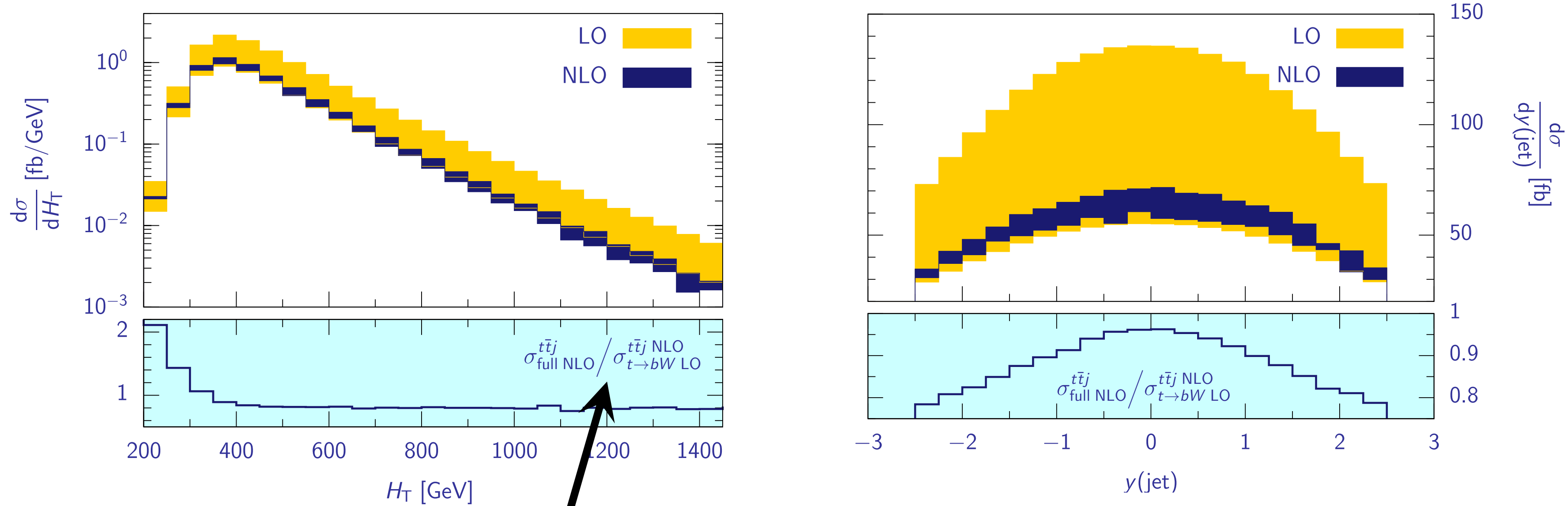
$$\sigma^{\mathrm{LO}}_{t\bar{t}+\mathrm{jet}} = 350.3\ \mathrm{fb} = 316.9(\mathrm{prod}) + 33.4(\mathrm{decay})\ \mathrm{fb}$$

x 1.02 x 1.21

$$\sigma^{\mathrm{NLO}}_{t\bar{t}+\mathrm{jet}} = 288\ \mathrm{fb} = 323(\mathrm{prod}) + 40.5(\mathrm{decay}) - 75.5(\mathrm{mixed})\ \mathrm{fb}$$



Phenomenology



(full NLO calculation) / (NLO calculation with LO decays)

$\Rightarrow$ **QCD corrections and radiation in top decays can have a significant effect on the shapes** (observable dependent)

Phenomenology

Comparison with parton showered calculation by

[Kardos,Papadopoulos, Trcosanyi]

(not a tuned comparison)

Tevatron,
semi-lept. channel

1.) Normalization

NLO in production
+ POWHEG BOX:

$$\sigma^{\mathrm{NLO+Herwig}} = 49 \text{ fb}$$

$$\sigma^{\mathrm{NLO+Pythia}} = 48 \text{ fb}$$

full NLO:

$$\sigma^{\mathrm{full\,NLO}} = 78.9\mathrm{fb} = 47.7(\mathrm{prod}) + 36.7(\mathrm{decay}) - 5.5(\mathrm{mix}) \text{ fb}$$

Per construction, a parton shower conserves the production probability.

Phenomenology

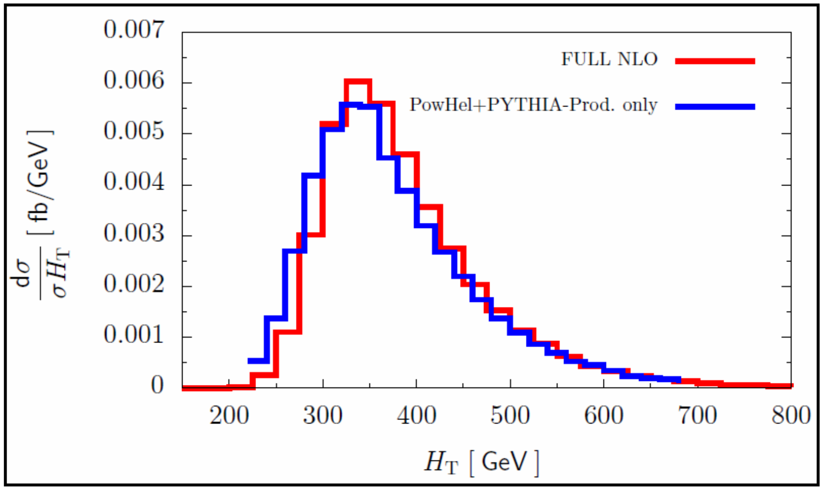
Comparison with parton showered calculation by

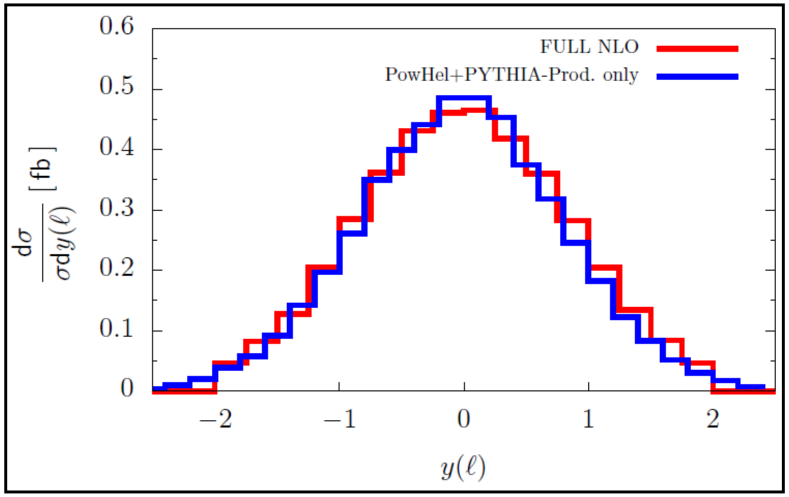
[Kardos,Papadopoulos, Trcosanyi]

(not a tuned comparison)

Tevatron,
semi-lept. channel

2.) Shape





Phenomenology

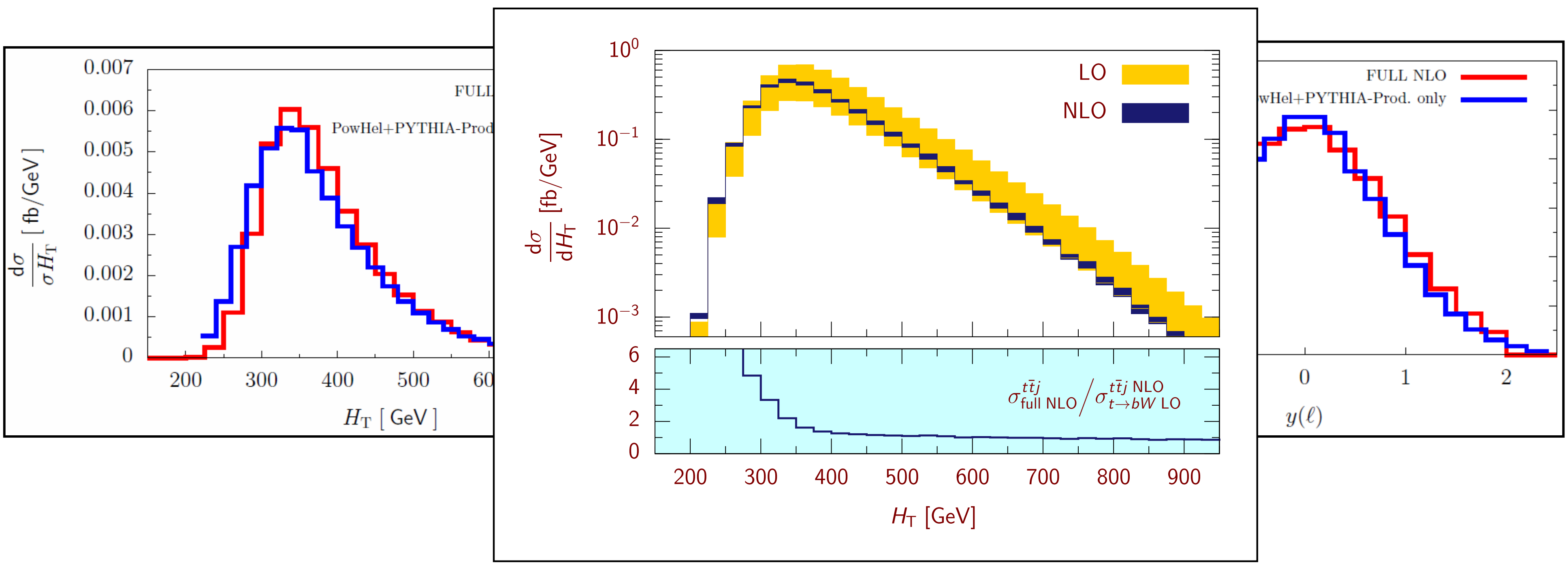
Comparison with parton showered calculation by

[Kardos,Papadopoulos, Trcosanyi]

(not a tuned comparison)

Tevatron,
semi-lept. channel

2.) Shape



Phenomenology

Forward-Backward Asymmetry

(Tevatron)

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$A_{\mathrm{LO}}^{t\bar{t}} = 0\% \qquad A_{\mathrm{NLO}}^{t\bar{t}} = +5\%$$

[Kühn,Rodrigo]

$$A_{\mathrm{LO}}^{t\bar{t}+\mathrm{jet}} = -8\% \qquad A_{\mathrm{NLO}}^{t\bar{t}+\mathrm{jet}} = -2\%$$

[Dittmaier,Weinzierl,Uwer]
[Melnikov,Schulze]

Phenomenology

Forward-Backward Asymmetry

(Tevatron)

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$A^{t\bar{t}}_{\mathrm{LO}} = 0\%$ $A^{t\bar{t}}_{\mathrm{NLO}} = +5\%$ [Kühn,Rodrigo]

$A^{t\bar{t}+\mathrm{jet}}_{\mathrm{LO}} = -8\%$ $A^{t\bar{t}+\mathrm{jet}}_{\mathrm{NLO}} = -2\%$ [Dittmaier,Weinzierl,Uwer] [Melnikov,Schulze]

$A^{t\bar{t}+\gamma}_{\mathrm{LO}} = -17\%$ $A^{t\bar{t}+\gamma}_{\mathrm{NLO}} = -11\%$ [Duan,Ma,Zhang,Han,Guo,Wang] [Melnikov,Scharf,Schulze]

$A^{t\bar{t}+2\mathrm{jet}}_{\mathrm{LO}} = -10\%$ $A^{t\bar{t}+2\mathrm{jet}}_{\mathrm{NLO}} = -5\%$ [Bevilacqua,Czakon,Papadopoulos,Worek]

Phenomenology

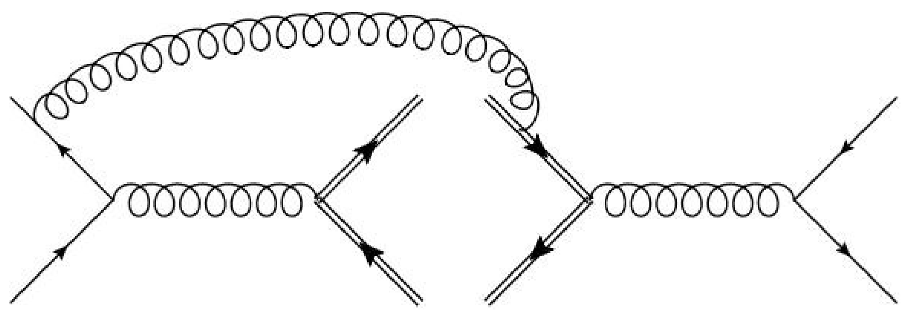
Forward-Backward Asymmetry

(Tevatron)

Is it possible to understand this seemingly universal shift of +5% ?

[Melnikov,M.S.]

LO QCD:



$$\sigma_+ - \sigma_- \sim \log(m_t/p_T^{\rm jet})\,\sigma_A$$

soft singularity

Phenomenology

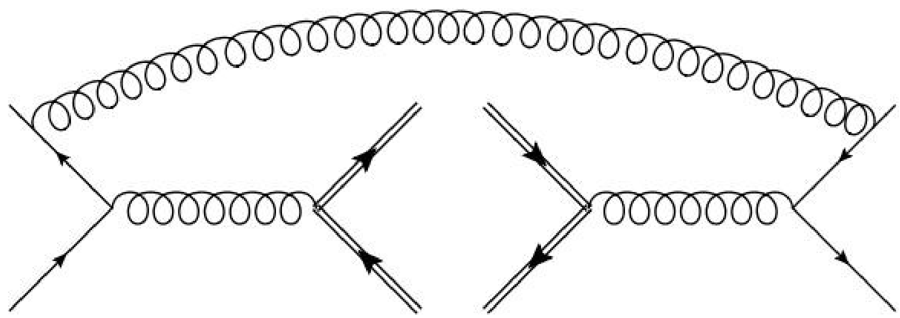
Forward-Backward Asymmetry

(Tevatron)

Is it possible to understand this seemingly universal shift of +5% ?

[Melnikov,M.S.]

LO QCD:



$$\sigma_+ - \sigma_- \sim \log(m_t/p_{\mathrm{T}}^{\mathrm{jet}})\,\sigma_A$$ soft singularity

$$\sigma_+ + \sigma_- \sim 2C_{\mathrm{F}}\frac{\alpha_s}{\pi}\log^2(m_t/p_{\mathrm{T}}^{\mathrm{jet}})\,\sigma_{t\bar{t}}$$ soft-coll. double log

$$\Rightarrow \quad A_{\mathrm{LO}}^{t\bar{t}+\mathrm{jet}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \sim \log^{-1}(m_t/p_{\mathrm{T}}^{\mathrm{jet}})$$

Phenomenology

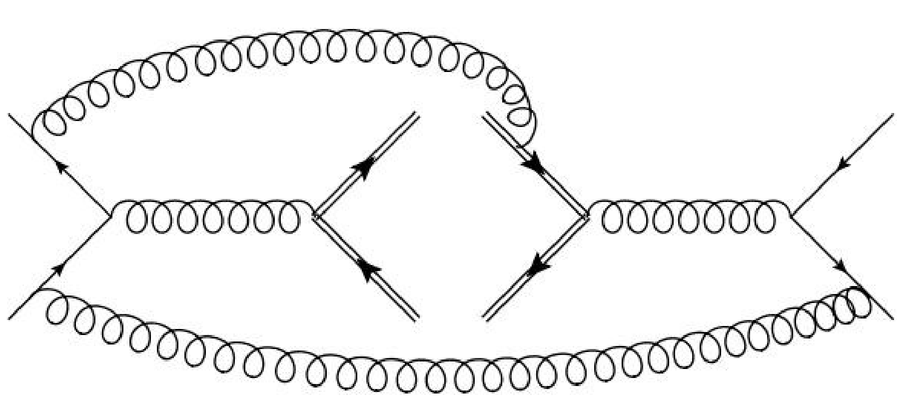
Forward-Backward Asymmetry

(Tevatron)

Is it possible to understand this seemingly universal shift of +5% ?

[Melnikov,M.S.]

NLO QCD:



$$\sigma_+ - \sigma_- \sim 2C_\mathrm{F}\frac{\alpha_s}{\pi}\,\log^2(m_t/p_\mathrm{T}^\mathrm{jet})\,A_\mathrm{NLO}^{t\bar{t}}\,\sigma_{t\bar{t}}$$

double log enhanced

$$A_\mathrm{NLO}^{t\bar{t}+\mathrm{jet}} = A_\mathrm{LO}^{t\bar{t}+\mathrm{jet}} + A_\mathrm{NLO}^{t\bar{t}}$$

with $A_\mathrm{NLO}^{t\bar{t}} = +5\%$

and $\lim_{p_\mathrm{T}^\mathrm{jet}\to 0} A_\mathrm{NLO}^{t\bar{t}+\mathrm{jet}} = A_\mathrm{NLO}^{t\bar{t}}$

SUMMARY

- ttb+jet is an important background for many New Physics searches and allows QCD studies at the LHC

- We have a flexible program to calculate NLO QCD corrections and jet radiation in production and decay

- Effects of corrections and radiation in decay can be significant

We are looking forward to comparisons with measurements