Top-quark pair-production with one jet and parton showering

Sven-Olaf Moch

Sven-Olaf.Moch@desy.de

DESY, Zeuthen

---

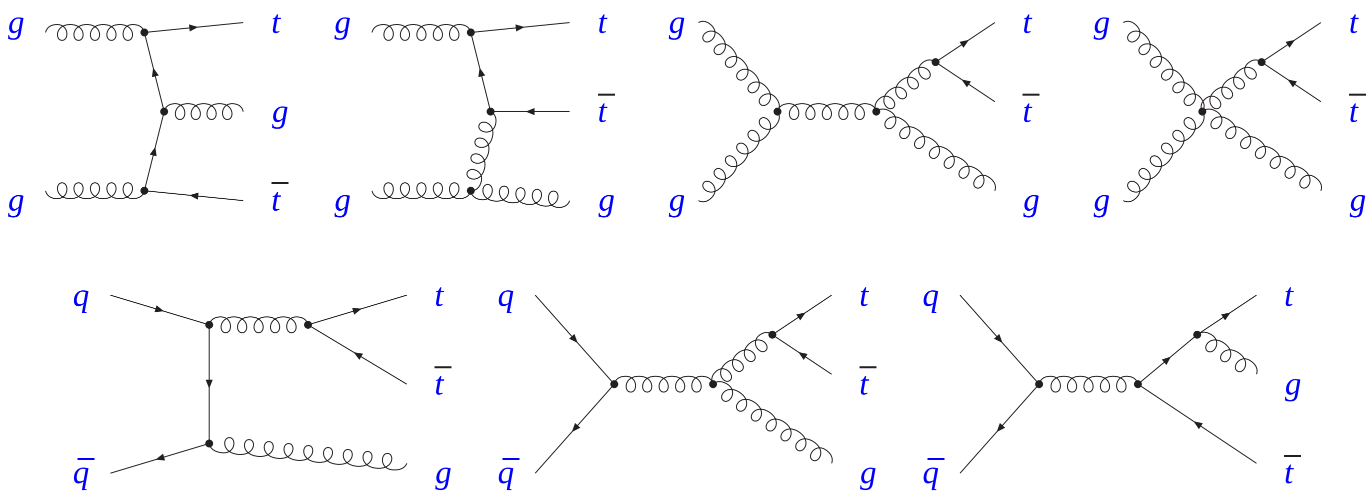
in collaboration with **S. Alioli** and **P. Uwer** on arXiv:1110.5251

Workshop DIS 2012 *Heavy Flavours Working Group*, Bonn, Mar 27, 2012

Top-quark pairs with one jet

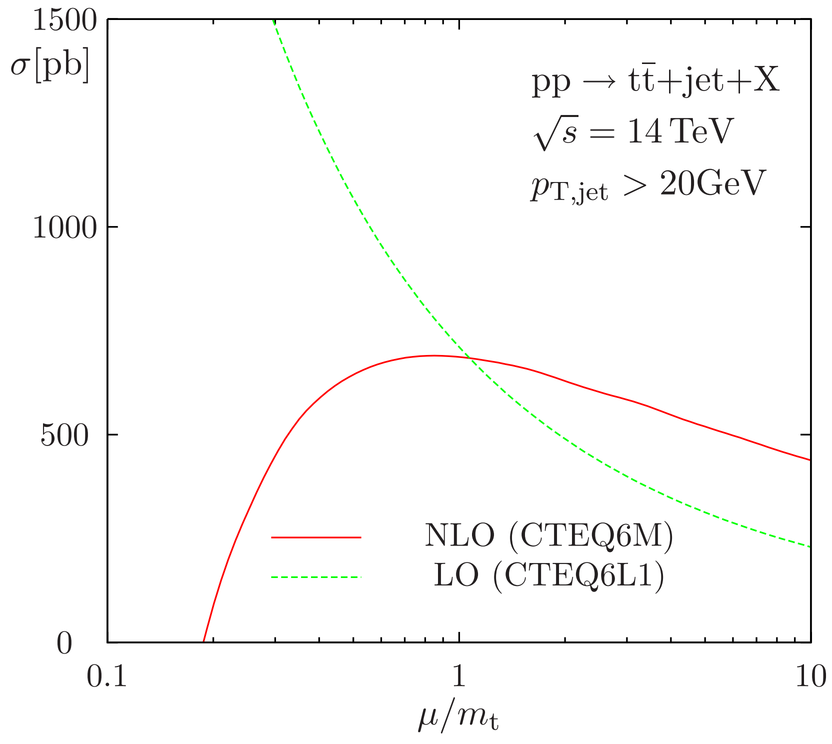
Production of $t\bar{t}$+jet at fixed order

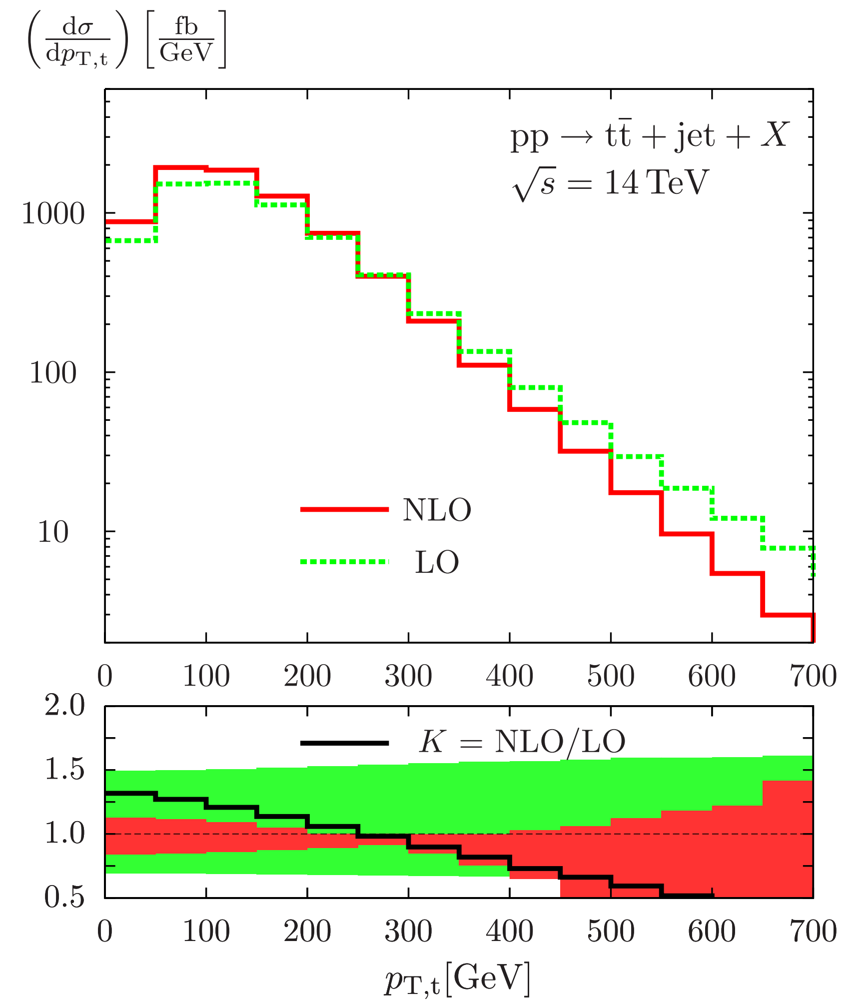
- LHC: large rates for production of $t\bar{t}$-pairs with additional jets
- Scale dependence at LO large



- Feynman diagrams (sample) for $t\bar{t}+$ jet production at LO

Production of $t\bar{t}+$ jet at NLO





- NLO QCD corrections Dittmaier, Uwer, Weinzierl '07-'08
  - scale dependence greatly reduced at NLO
  - corrections for total rate at scale $\mu_r = \mu_f = m_t$ are almost zero
  - transverse-momentum distributions of top-quark $p_{T,t}$ along with K-factor and scale variation $m_t/2 \leq \mu \leq 2m_t$

Monte Carlo and parton showers at NLO

- Merging of fixed order NLO with parton shower Monte Carlo
  Frixione, Webber '02, Nason '04
  - combining accuracy of exact hard matrix elements for large angle scattering at NLO with soft/collinear emission of parton shower
- POWHEG BOX as standard interface to parton shower programs PYTHIA or HERWIG Alioli, Nason, Oleari, Re '10
- Production of $t\bar{t}+$ jet and parton showers
  Kardos, Papadopoulos, Trocsanyi '11, Alioli, S.M., Uwer '11

Implementation

- Event generation with cut on $p_t^{\mathrm{gen}} \simeq 1$ GeV
- Alternative option for soft and collinear divergences at Born level: generation of weighted events with Born suppression factor
  $\bar{B}_{\mathrm{supp}} = \bar{B} \times F(p_t)$ Alioli, Nason, Oleari, Re '10

$$F(p_t) = \left(\frac{p_t^2}{p_t^2 + (p_t^{\mathrm{supp}})^2} \right)^n$$

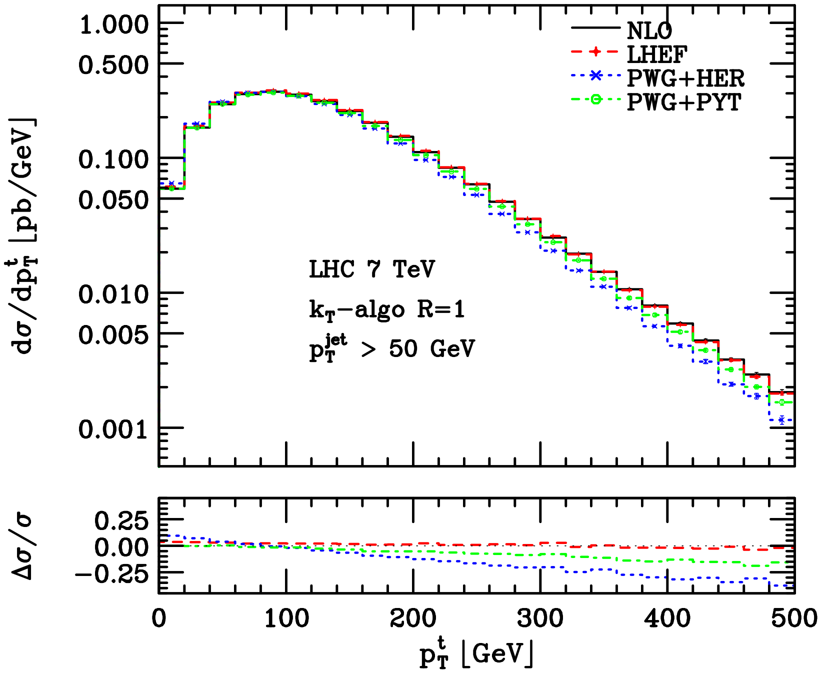
Quality check

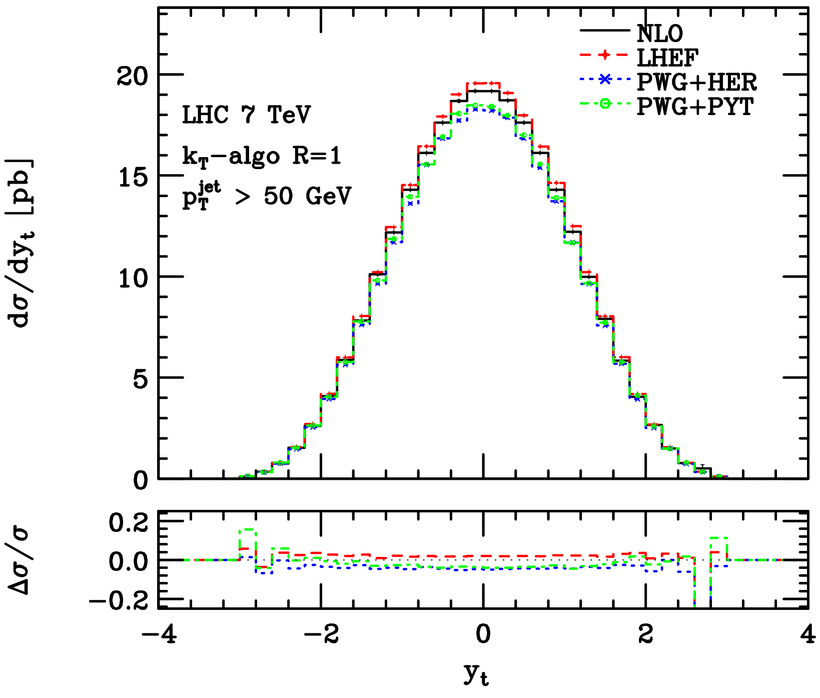
- Independence of NLO cross section on generation cut $p_t^{\rm gen}$ and on Born suppression factor $p_t^{\rm supp}$ for analysis cut $p_t^{\rm an}$ Alioli, S.M., Uwer '11
  - inclusive k_t-algorithm with $R = 1$ for $\mu_r = \mu_f = m_t = 174$ GeV and CTEQ6M PDFs

	$p_t^{\rm gen}$ [GeV]	$p_t^{\rm supp}$ [GeV]	$p_t^{\rm an}$ [GeV]	$\sigma^{\rm NLO}$ [pb]
	0	20	20	1.793 ± 0.002
	2	0	20	1.790 ± 0.001
TEV 1.96 TeV	2	20	20	1.791 ± 0.002
	2	200	20	1.793 ± 0.002
	5	0	20	1.782 ± 0.001
	5	20	20	1.785 ± 0.001
	0	400	50	52.6 ± 0.5
	5	400	50	52.7 ± 0.5
LHC 7 TeV	5	100	50	53.1 ± 0.2
	10	0	50	52.9 ± 0.4
	10	400	50	52.5 ± 0.1
	15	0	50	52.6 ± 0.4
	0	400	50	379.8 ± 1.6
LHC 14 TeV	5	100	50	376.1 ± 0.2
	5	400	50	377.2 ± 1.6

Production $t\bar{t}+$ jet and parton shower (I)

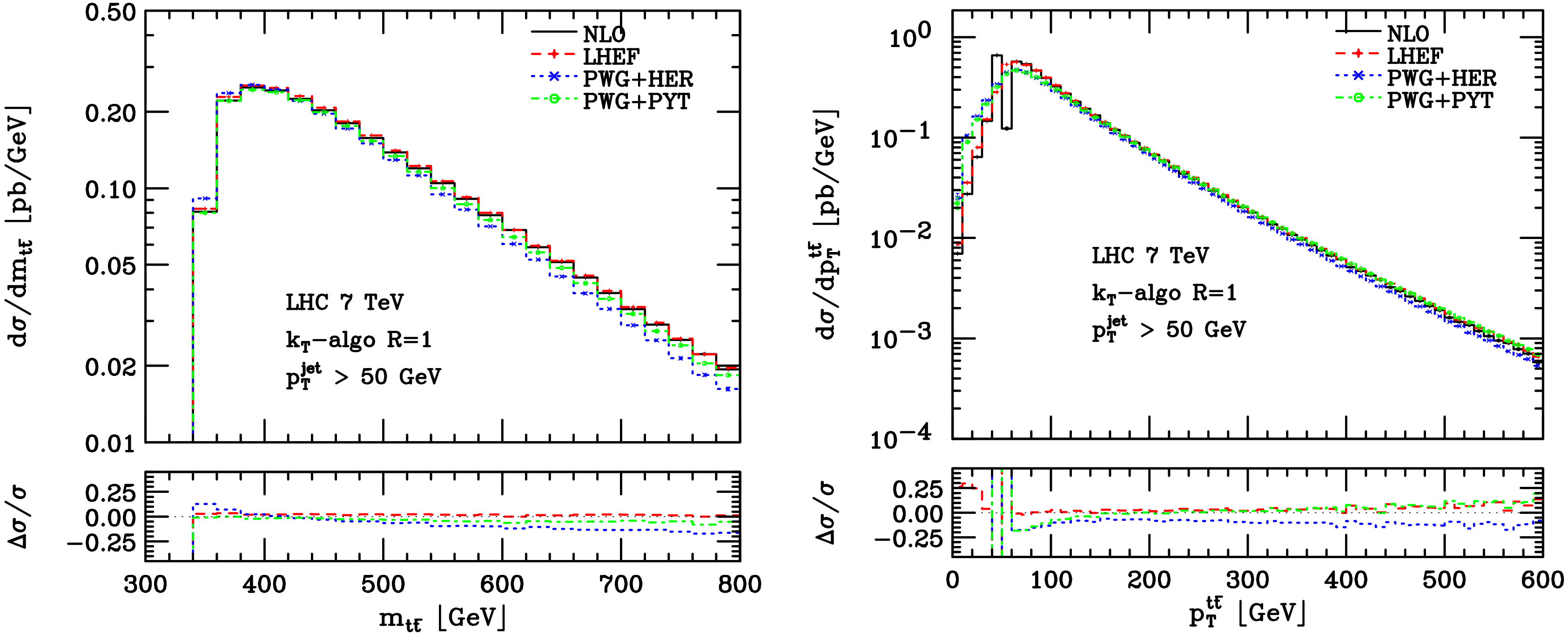
- Differential distributions in top-quark's transverse momentum p_T^t and rapidity y_t at LHC7
  - comparision of NLO, LHEF for POWHEG hardest emission without showering, and POWHEG with shower/hadronization with HERWIG or PYTHIA





Production $t\bar{t}+$ jet and parton shower (II)

- Differential distributions as function of $t\bar{t}$-pair invariant mass $m_{t\bar{t}}$ and transverse momentum $p_T^{t\bar{t}}$ at LHC7



Asymmetries for $t\bar{t}+$ jet: Tevatron

- Top-quark forward-backward asymmetry A_{FB} in $t\bar{t}+$ jet sample at Tevatron with $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$
  - incl. k_t-algorithm with $R = 1$ and $p_t^{\text{jet}} > 20\ \text{GeV}$ minimum jet cut

$$A_{\text{FB}}^{t} = \frac{1}{\sigma}\left(\int\limits_{y_t>0} d\sigma - \int\limits_{y_t<0} d\sigma\right)\,, \qquad A_{\text{FB}}^{t\bar{t}} = \frac{1}{\sigma}\left(\int\limits_{\Delta y_{t\bar{t}}>0} d\sigma - \int\limits_{\Delta y_{t\bar{t}}<0} d\sigma\right)$$

- initial $p\bar{p}$ state is CP eigenstate at Tevatron and no CP violating effects in QCD: $\dfrac{d\sigma}{dy_t}(y_t) = \dfrac{d\sigma}{dy_{\bar{t}}}(-y_{\bar{t}})$

Asymmetries for $t\bar{t}+$ jet: Tevatron

- $A_{\rm FB}^{t\bar{t}} = A_{\rm FB}^{t}$ in $t\bar{t}$ rest frame; $A_{\rm FB}^{t\bar{t}} > A_{\rm FB}^{t}$ in lab frame

Tevatron 1.96 TeV	NLO [%]	LHEF [%]	PWG+HER [%]	PWG+HER+UE [%]	PWG+PYT [%]	PWG+PYT+MPI [%]
$A_{\rm FB}^{t}$ total	-2.98 ± 0.04	-2.95 ± 0.05	-1.75 ± 0.11	-1.70 ± 0.11	-1.49 ± 0.11	-1.36 ± 0.11
$A_{\rm FB}^{t}$, $\|y_t\| < 1.0$	-2.60 ± 0.04	-2.55 ± 0.05	-1.51 ± 0.12	-1.53 ± 0.11	-1.31 ± 0.12	-1.22 ± 0.12
$A_{\rm FB}^{t}$, $\|y_t\| \geq 1.0$	-6.38 ± 0.19	-6.51 ± 0.15	-3.79 ± 0.35	-3.15 ± 0.34	-2.99 ± 0.35	-2.58 ± 0.34
$A_{\rm FB}^{t}$, $\|m_{t\bar{t}}\| < 450$ GeV	-1.90 ± 0.06	-1.80 ± 0.06	-1.24 ± 0.14	-1.24 ± 0.13	-0.81 ± 0.14	-1.00 ± 0.14
$A_{\rm FB}^{t}$, $\|m_{t\bar{t}}\| \geq 450$ GeV	-4.70 ± 0.06	-4.77 ± 0.08	-2.70 ± 0.19	-2.54 ± 0.18	-2.66 ± 0.18	-1.98 ± 0.18
$A_{\rm FB}^{t}$, $p_{\rm T}^{t\bar{t}} \geq 10$ GeV	-2.95 ± 0.04	-2.93 ± 0.05	-2.64 ± 0.06	-2.59 ± 0.06	-2.58 ± 0.06	-2.39 ± 0.06
$A_{\rm FB}^{t}$, $p_{\rm T}^{t\bar{t}} \geq 20$ GeV	-2.41 ± 0.05	-2.94 ± 0.05	-2.80 ± 0.05	-2.80 ± 0.05	-2.85 ± 0.05	-2.81 ± 0.05
$A_{\rm FB}^{t}$, $p_{\rm T}^{t\bar{t}} \geq 35$ GeV	-3.90 ± 0.06	-3.85 ± 0.05	-3.54 ± 0.06	-3.55 ± 0.06	-3.67 ± 0.06	-3.63 ± 0.06
$A_{\rm FB}^{t}$, $p_{\rm T}^{t\bar{t}} \geq 50$ GeV	-4.31 ± 0.07	-4.33 ± 0.06	-4.00 ± 0.07	-4.02 ± 0.07	-4.19 ± 0.07	-4.19 ± 0.07
$A_{\rm FB}^{t}$, $p_{\rm T}^{t\bar{t}} \geq 75$ GeV	-4.88 ± 0.08	-4.62 ± 0.08	-4.33 ± 0.09	-4.29 ± 0.09	-4.59 ± 0.09	-4.56 ± 0.09

Asymmetries for $t\bar{t}+$ jet: Tevatron

- $A_{\rm FB}^{t\bar{t}} = A_{\rm FB}^{t}$ in $t\bar{t}$ rest frame; $A_{\rm FB}^{t\bar{t}} > A_{\rm FB}^{t}$ in lab frame

Tevatron 1.96 TeV	NLO [%]	LHEF [%]	PWG+HER [%]	PWG+HER+UE [%]	PWG+PYT [%]	PWG+PYT+MPI [%]
$A_{\rm FB}^{t\bar{t}}$ total	-4.40 ± 0.04	-4.34 ± 0.05	-2.80 ± 0.11	-2.54 ± 0.11	-2.22 ± 0.11	-1.84 ± 0.11
$A_{\rm FB}^{t\bar{t}}$, $\lvert\Delta y_{t\bar{t}}\rvert < 1.0$	-2.70 ± 0.04	-2.62 ± 0.05	-1.71 ± 0.11	-1.91 ± 0.11	-1.39 ± 0.11	-1.16 ± 0.11
$A_{\rm FB}^{t\bar{t}}$, $\lvert\Delta y_{t\bar{t}}\rvert \geq 1.0$	-19.48 ± 0.18	-19.54 ± 0.22	-10.52 ± 0.52	-9.75 ± 0.51	-9.22 ± 0.52	-7.54 ± 0.51
$A_{\rm FB}^{t\bar{t}}$, $\lvert m_{t\bar{t}}\rvert < 450$ GeV	-3.59 ± 0.06	-3.51 ± 0.06	-2.67 ± 0.14	-2.36 ± 0.13	-1.74 ± 0.14	-1.63 ± 0.14
$A_{\rm FB}^{t\bar{t}}$, $\lvert m_{t\bar{t}}\rvert \geq 450$ GeV	-5.70 ± 0.06	-5.66 ± 0.08	-3.03 ± 0.19	-2.88 ± 0.18	-3.06 ± 0.18	-2.20 ± 0.18
$A_{\rm FB}^{t\bar{t}}$, $p_{\rm T}^{t\bar{t}} \geq 10$ GeV	-4.35 ± 0.04	-4.32 ± 0.05	-3.98 ± 0.06	-3.86 ± 0.06	-3.72 ± 0.06	-3.51 ± 0.06
$A_{\rm FB}^{t\bar{t}}$, $p_{\rm T}^{t\bar{t}} \geq 20$ GeV	-3.71 ± 0.05	-4.29 ± 0.05	-4.22 ± 0.05	-4.18 ± 0.05	-4.15 ± 0.05	-4.11 ± 0.05
$A_{\rm FB}^{t\bar{t}}$, $p_{\rm T}^{t\bar{t}} \geq 35$ GeV	-5.72 ± 0.06	-5.52 ± 0.05	-5.16 ± 0.06	-5.17 ± 0.06	-5.21 ± 0.06	-5.21 ± 0.06
$A_{\rm FB}^{t\bar{t}}$, $p_{\rm T}^{t\bar{t}} \geq 50$ GeV	-6.25 ± 0.07	-6.11 ± 0.06	-5.70 ± 0.07	-5.74 ± 0.07	-5.85 ± 0.07	-5.92 ± 0.07
$A_{\rm FB}^{t\bar{t}}$, $p_{\rm T}^{t\bar{t}} \geq 75$ GeV	-6.62 ± 0.08	-6.45 ± 0.08	-5.99 ± 0.09	-5.94 ± 0.09	-6.27 ± 0.09	-6.25 ± 0.09

Asymmetries for $t\bar{t}+$ jet: LHC

- Top-quark charge asymmetry A_C in $t\bar{t}+$ jet sample at LHC7
  - incl. k_t-algorithm with $R = 1$ and $p_t^{\rm jet} > 50$ GeV minimum jet cut
  - $\Delta|x| = |x_t| - |x_{\bar{t}}|$ and $x = \eta$ (pseudo-rapidity) or $x = y$ (rapidity)
    ATLAS-CONF-2011-106, CMS-PAS-TOP-11-014

$$A_C^x = \frac{1}{\sigma}\left(\int\limits_{\Delta|x|>0} d\sigma - \int\limits_{\Delta|x|<0} d\sigma \right)$$

LHC 7 TeV	NLO [%]	LHEF [%]	PWG+HER [%]	PWG+HER+UE [%]	PWG+PYT[%]	PWG+PYT+MPI [%]
A_C^η	0.19 ± 0.09	0.18 ± 0.06	0.46 ± 0.10	0.26 ± 0.11	0.40 ± 0.11	0.57 ± 0.11
A_C^y	0.51 ± 0.09	0.47 ± 0.06	0.73 ± 0.10	0.52 ± 0.11	0.66 ± 0.11	$0.76 + 0.11$

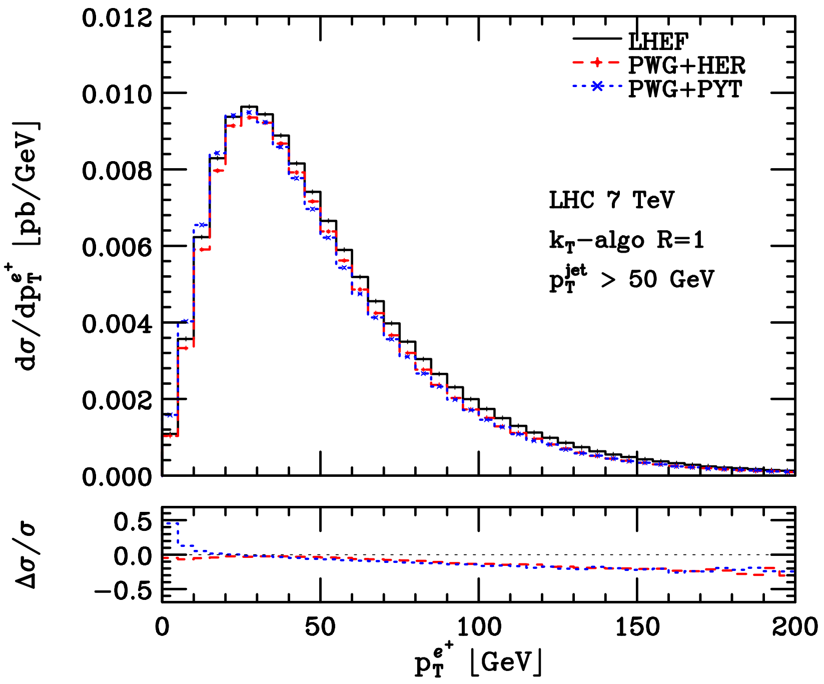
- Sizeable effects on asymmetries in $t\bar{t}+$ jet sample due to parton showers (both Tevtron and LHC)

Top-quark decay

- Implementation of top-quark decay in NLO merged with parton showers Frixione, Laenen, Motylinski, Webber ‘07
  - generate events with stable t, $\bar{t}$ (un-decayed events) through POWHEG machinery
  - generate decay products of t, $\bar{t}$ according to matrix element for full production and decay process (decayed events)
  - reshuffle momenta of t, $\bar{t}$ decay products $\longrightarrow$ obtain off-shell t, $\bar{t}$ and W bosons
- Concentrate on the di-leptons channel from $t\bar{t}$ decay only

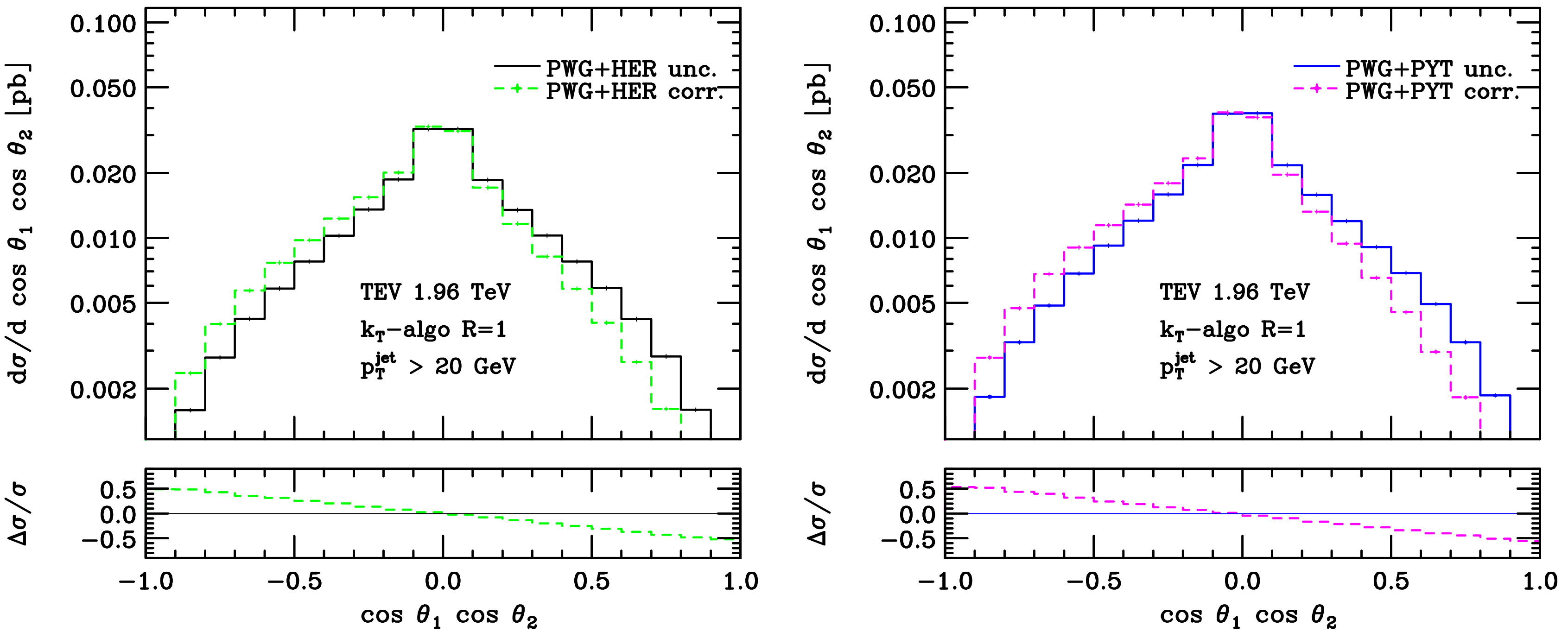
Top-quark decay

- Differential cross sections for positively charged lepton transverse momenta at LHC7
  - shower effects are rather small; no dependence on top-quark spin expected



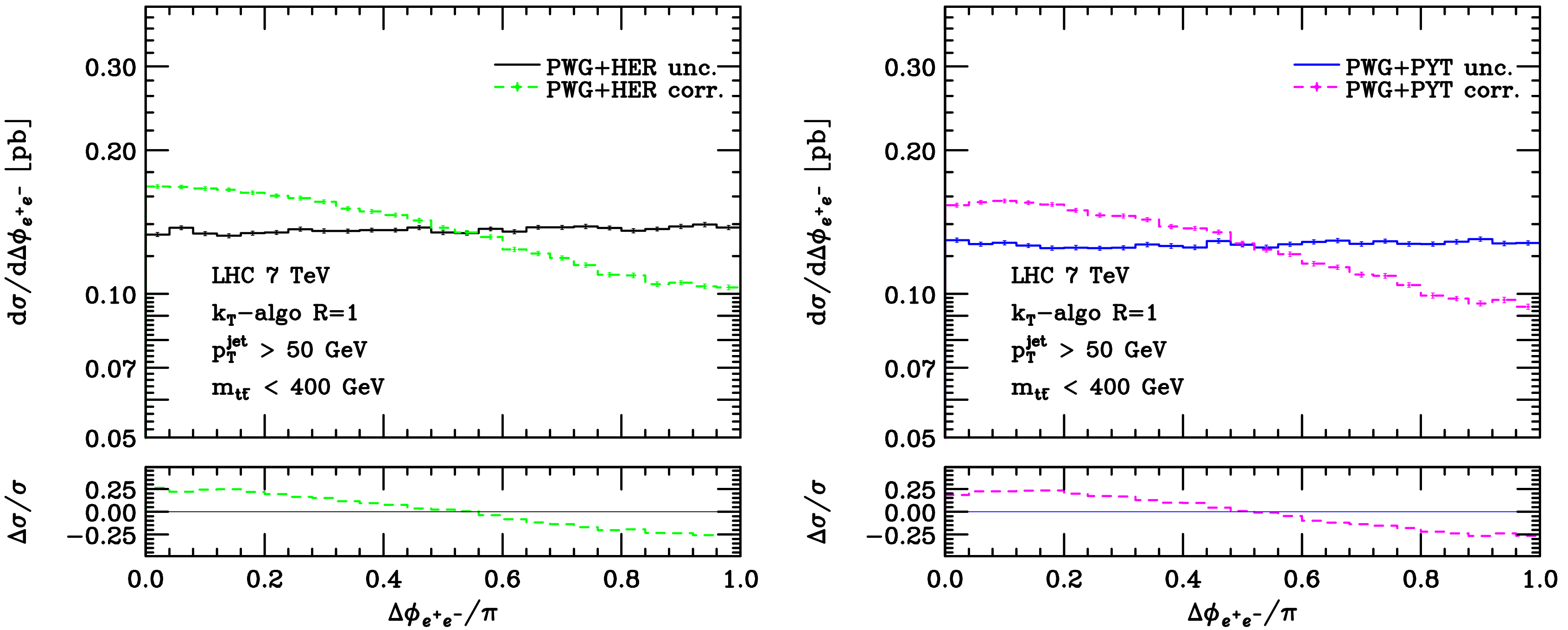
Spin-correlations (I)

- Spin correlation effects $t\bar{t}$ require spin quantization axis for t and $\bar{t}$ (definition of reference frames) Bernreuther, Brandenburg, Si, Uwer '01
  - example of observable $\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2}$
  - angles θ_1 (θ_2) between directions of flights of leptons coming from the decayed top-quark in the t ($\bar{t}$) rest frame and quantization axis
- Tevatron with effect of parton shower programs HERWIG and PYTHIA



Spin-correlations (II)

- Azimuthal distance between leptons coming from t and $\bar{t}$ depend mildly on spin-correlations
- LHC7
  - effect of spin correlations when interfacing to HERWIG and PYTHIA programs

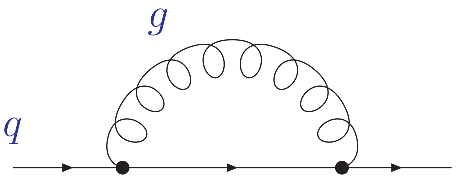


Mass measurement

Pole mass

- Based on (unphysical) concept of top-quark being a free parton

$$\not p - m_q - \Sigma(p, m_q)\Big|_{p^2=m_q^2}$$



  - heavy-quark self-energy $\Sigma(p, m_q)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{QCD})$
- Definition of pole mass ambiguous up to corrections $\mathcal{O}(\Lambda_{QCD})$

Running quark masses

- $\overline{MS}$ mass definition $m(\mu_R)$ realizes running mass (scale dependence)
  - short distance mass probes at scale of hard scattering
    $m_{\text{pole}} = m_{\text{short distance}} + \delta m$
  - conversion between pole mass and $\overline{MS}$ mass definition in perturbation theory: $m = m(\mu_R)\left(1 + a_s(\mu_R)d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$

Mass measurement with $t\bar{t} + jet$-samples

- Mass measurement with new observable Alioli, Fuster, Irles, S.M., Uwer, Vos
  - define normalized-differential $t\bar{t} + jet$ cross section

$$\frac{dn_3}{d\rho_s}(m_{top}, \mu, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1jet}} \frac{d\sigma_{t\bar{t}+1jet}}{d\rho_s}(m_{top}, \mu, \rho_s)$$

  - variable $\rho_s = \frac{2 \cdot m_0}{\sqrt{s_{t\bar{t}+1jet}}}$ with $m_0 = 170\,\mathrm{GeV}$ and invariant mass of multi-jet system $\sqrt{s_{t\bar{t}+1jet}}$

Upshot

- Independent determination of top-quark mass m_t
  - alternative to kinematic reconstruction and extraction from total cross section

Summary

- Production of $t\bar{t}$+jet at LHC important
  - merging with parton showers shows good stability
  - important effects of parton showers for asymmetries in $t\bar{t}$+jet-samples
- Phenomenology
  - new observables for mass measurement
  - study of spin-correlations feasible
- Implementation in POWHEGBOX
  - code release for public use soon