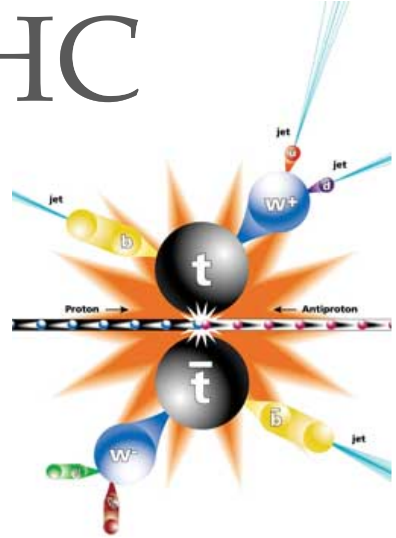
Theoretical predictions for top anti-top production at NLO

Malgorzata Worek
Wuppertal Uni.

Alliance Top Quark Workshop, 22-23 March 2012, Berlin

top anti-top at the LHC



- One of the first measurements carried out by LHC
- Produced predominantly through strong interactions
- Decays without forming hadrons via $t \rightarrow W b$
- Distinguished by its large mass
- Is the top quark mass generated by the Higgs mechanism ?
- Does it play more fundamental role ?

- LHC tt factory! Large statistics - 10^7 tt pairs per year
- Experimental uncertainty reached 6% (!) level

- Tests of QCD, intrinsic properties of top and its EW interactions
- Accurate determination of σ_{tt} provides indirect determination of m_t
- Anomalies in the total rate would indicate non-QCD production channels
- Must be confirmed by precise studies of the top quark distributions
- Distributions would be distorted by the presence of anomalous couplings or s-channel resonances expected in several BSM scenarios

Why LO is not enough ?

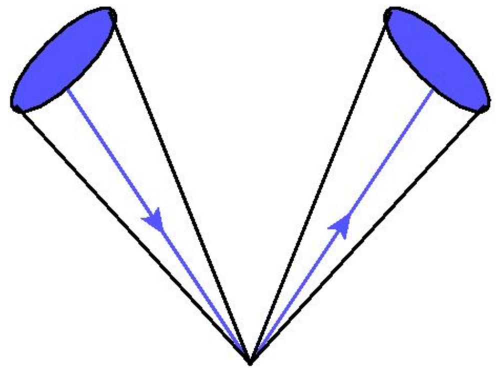
- Many partons in the final state, all off-shell effects, interferences, non-resonance contributions, full color information, spin correlations, etc.
- Standard Model and beyond tools

ALPGEN, COMPHEP, HELAC-PHEGAS, MADEVENT, SHERPA, WHIZARD, ...

- Predictions can be matched with General purpose Monte Carlo programs (parton shower, hadronization, multiple interactions, hadrons decays, etc.)

HERWIG, HERWIG++, PYTHIA 6.4, PYTHIA 8.1, SHERPA, ...

- High sensitivity to unphysical input scales
- Huge theoretical errors related to the scale dependence
- Very crude description of differential distributions
- Very simplified description of jets: parton = jet



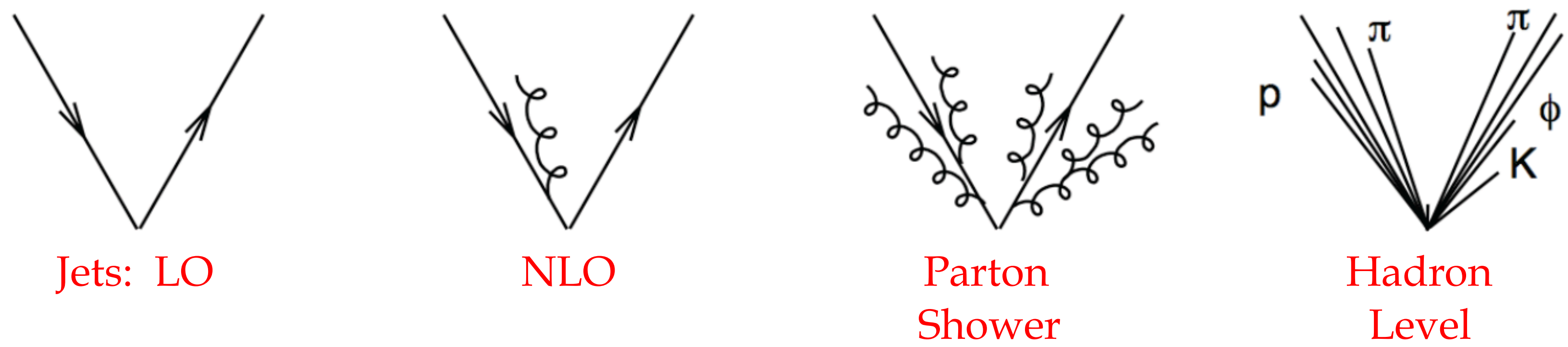
JETS: LO

At least NLO QCD

- Stabilizing the scale in the QCD input parameters: α_s and PDFs
- More reliable theoretical error related to the scale dependence
- Normalization and shape of distributions first known at NLO

- 2 $\rightarrow$ 4(5) processes are many scale processes:
  - Z + 3j, ttH $\rightarrow$ ttbb, ttbb, bbbb, 4j, W + 4j
  - better understanding of how to choose scale
  - dynamic variables that depend on the event structure

- Improved description of jets



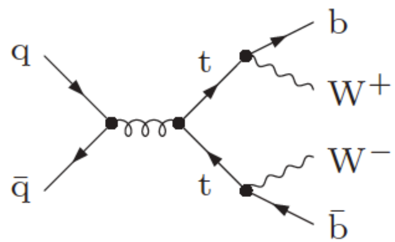
The strongest argument in support of NLO calculations is their success in an accurate description of the LEP and TeVatron data !

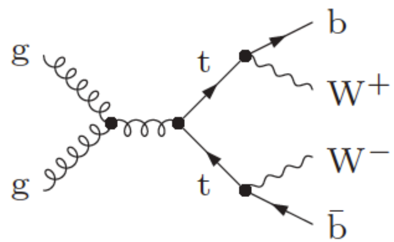
In this talk

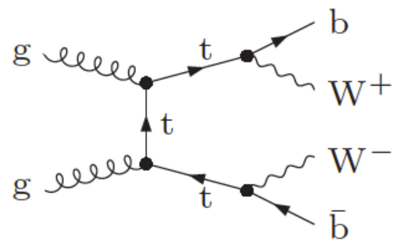
- A good theoretical understanding of top pair production is crucial for many analyses at Tevatron and LHC
  - top a signal (precise measurement of top quark properties)
  - top a background in new physics searches (Higgs boson, BSM)

- Top pair phenomenology has been widely investigated since many years with impressive progress in several directions (NLO, NNLO, resummation...)

- In this talk: few (quite recent) selected topics which show current status of NLO predictions at the LHC and forward-backward asymmetry at the TeVatron for for processes:
  - pp → tt + X
  - pp → tt + 1 jet + X
  - pp → tt + 2 jets + X







top anti-top @ NLO QCD

- Narrow-width approximation
- NLO corrections to both production and decay, neglecting non-factorizable corrections, including spin correlations at NLO
  - Double differential angular distributions to probe spin correlations of top

W. Bernreuther, A. Brandenburg, Z. G. Si and P. Uwer (2004)

  - Flexible Monte Carlo implementation, fully differential level
  - Spin correlations of top anti-top via decay products
  - pp → tt + X → WWbb + X → lν lν bb + X (di-lepton)
  - pp → tt + X → WWbb + X → ud lν bb + X (lepton + jet)

K. Melnikov and M. Schulze (2009)

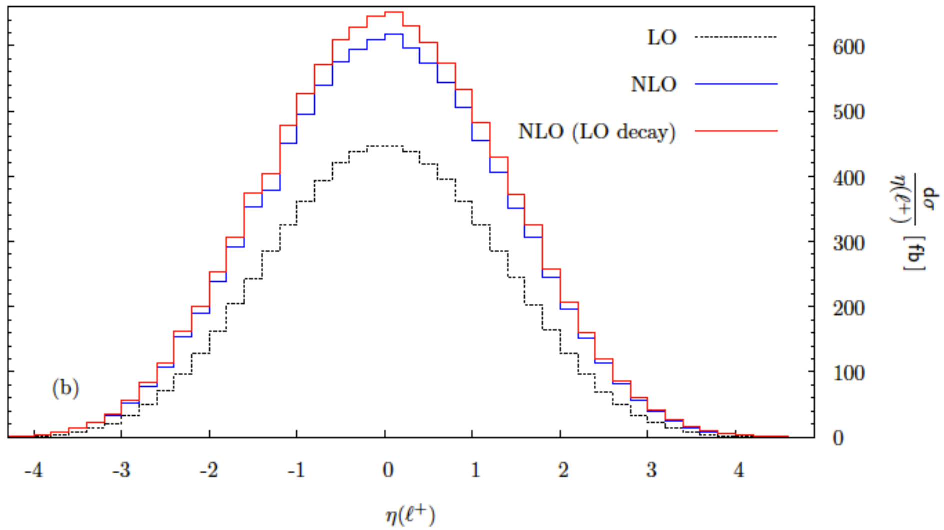
- Results of NLO+PS matching available since quite some time
  - MC@NLO
  - POWHEG

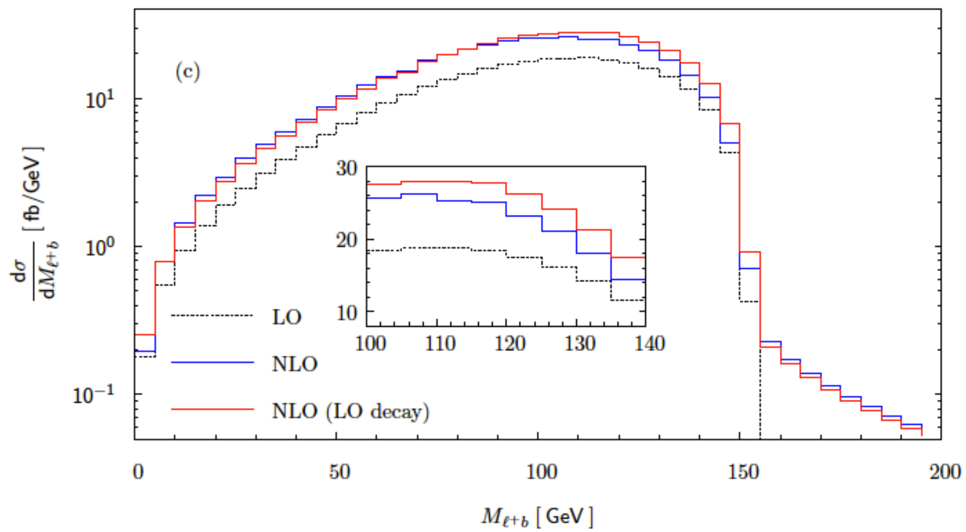
S. Frixione, P. Nason, B. R. Webber (2003)
S. Frixione, P. Nason, G. Ridolfi (2007)

top anti-top @ NLO in NWA

- Predictions at LO and NLO with and without corrections to the decay
- pp → tt + X → WWbb + X → lν lν bb + X

@ LHC 10 TeV





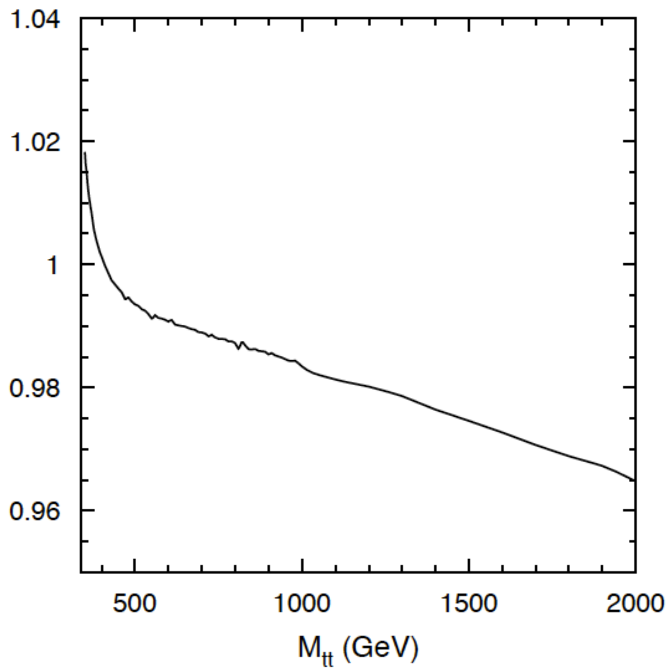
K. Melnikov and M. Schulze (2009)

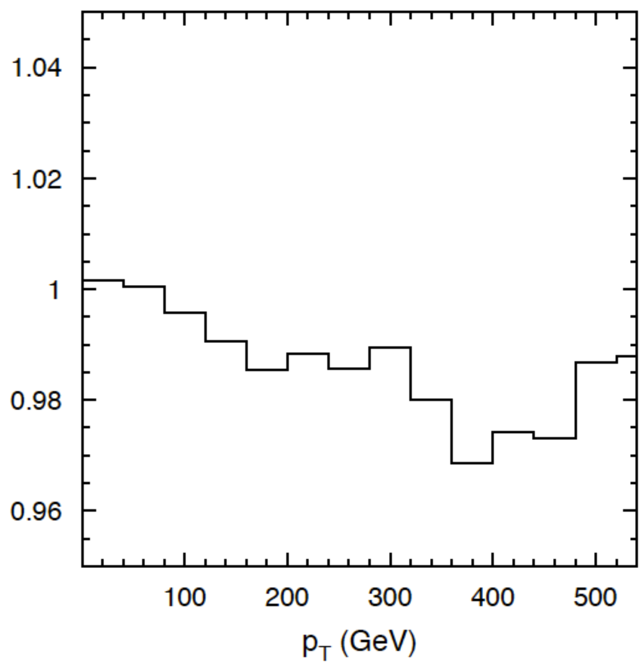
Mixed QCD-EW Corrections

- NLO order in the strong and weak gauge couplings (NLOW with NWA)
- The ratio of the distributions evaluated at NLOW and NLO: m_{tt} and $p_T(t)$
- pp → tt + X → WWbb + X → lν lν bb + X

W. Bernreuther, Z. G. Si (2010)

@ LHC 14 TeV

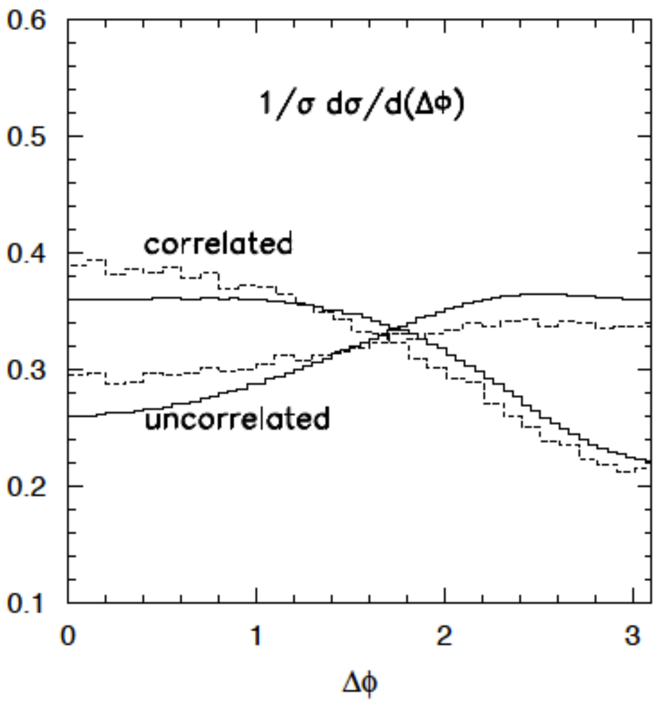




Mixed QCD-EW Corrections

- NLO order in the strong and weak gauge couplings (NLOW), with NWA
- $pp \rightarrow tt + X \rightarrow WWbb + X \rightarrow l\nu\ l\nu\ bb + X$

W. Bernreuther, Z. G. Si (2010)



- Effect of top anti-top spin correlations

- Azimuthal angle distribution of two leptons
- With and without top anti-top spin correlations
- Solid line is LO
- Dashed line is NLOW

@ LHC 14 TeV

Beyond NWA

- Complete NLO description of the production of top anti-top pairs including interferences, off-shell effects, and non-resonant backgrounds, spin correlations
- State of the art description of $t\bar{t}$ process
- Two independent calculations with per-mille agreement

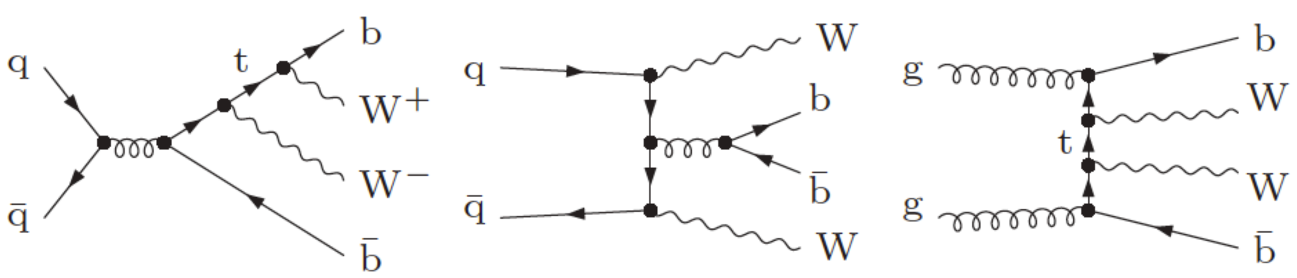
$pp \to WWb\bar{b} + X \to l\nu\ l\nu\ b\bar{b} + X$

A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini (2011)

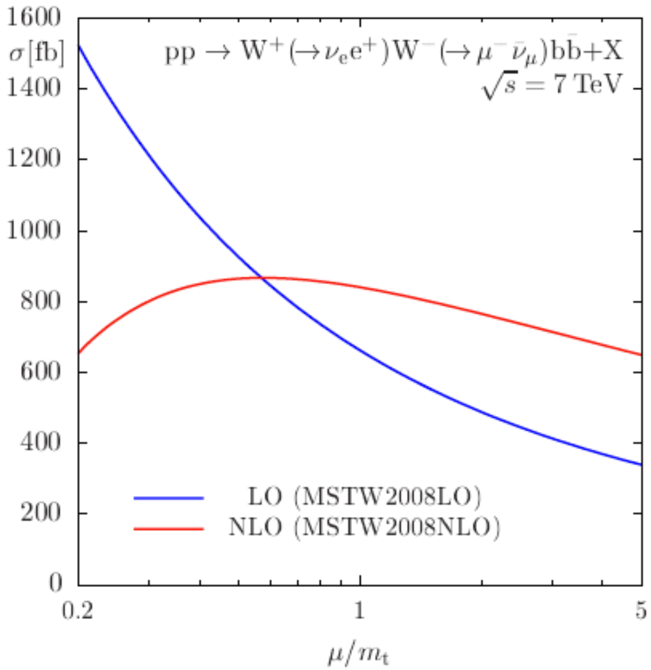
$pp \to l\nu\ l\nu\ b\bar{b} + X$

G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, M. Worek (2011)

Finite-width effects on $\sigma_{t\bar{t}}$ small, around 1%, both at the Tevatron and the LHC



Beyond NWA



NLO QCD Corrections
K = NLO/LO = **1.47**

Scale dependence
LO **37%** → NLO **9%**

@ LHC 7 TeV & 10 TeV

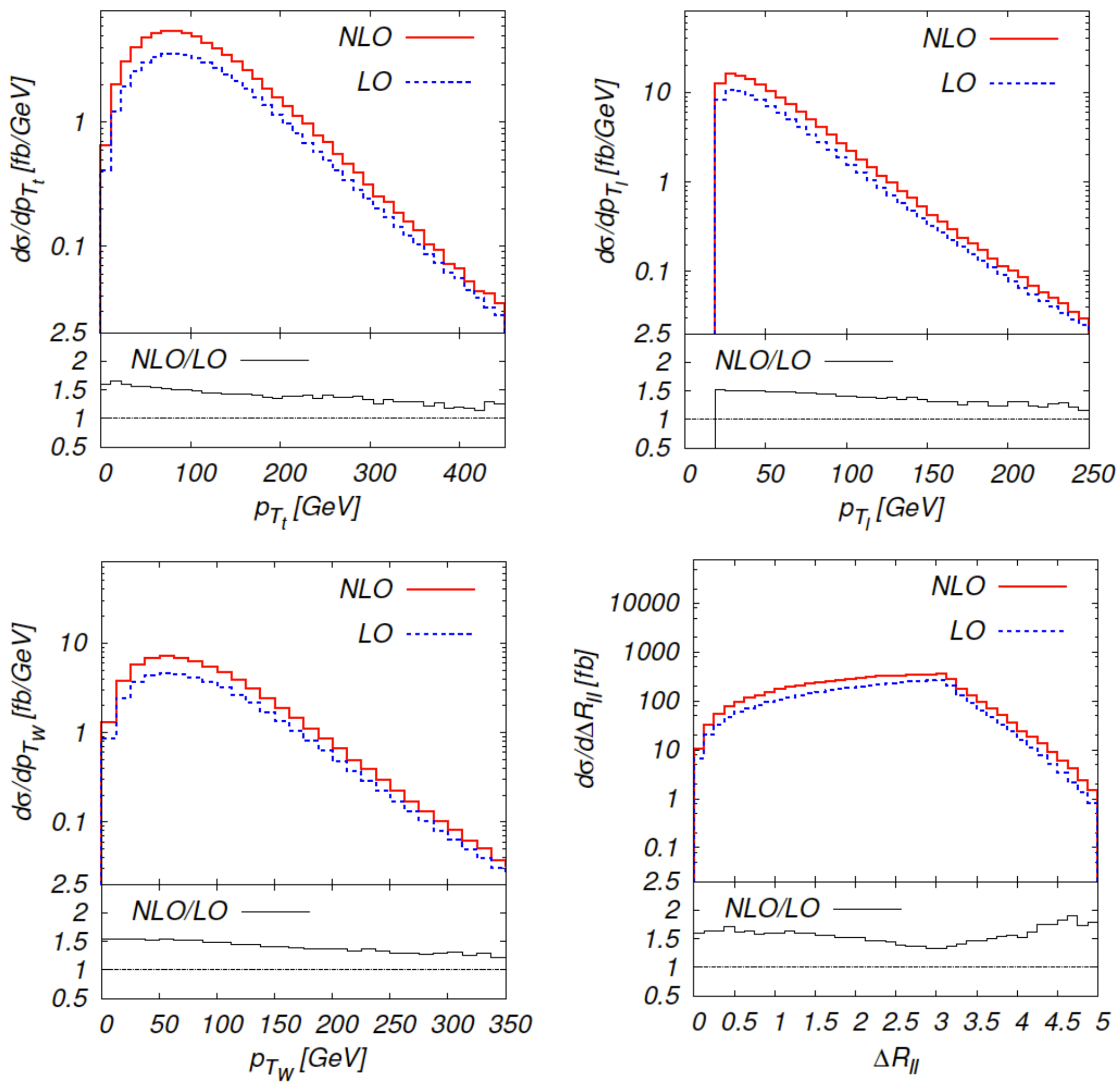
Algorithm	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=1}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=0.01}$ [fb]
anti-k_T	550.54 ± 0.18	808.46 ± 0.98	808.29 ± 1.04
k_T	550.54 ± 0.18	808.67 ± 0.97	808.86 ± 1.03
C/A	550.54 ± 0.18	808.74 ± 0.97	808.28 ± 1.03

Algorithm	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=1}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=0.01}$ [fb]
anti-k_T	1394.72 ± 0.75	1993.3 ± 2.5	1993.9 ± 2.7
k_T	1394.72 ± 0.75	1995.2 ± 2.5	1994.3 ± 2.7
C/A	1394.72 ± 0.75	1995.0 ± 2.5	1994.3 ± 2.7

- ❑ Double-, single- and non-resonant top quark contributions
- ❑ Complex-mass scheme for unstable top
- ❑ W gauge bosons are treated off-shell

G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, M. Worek (2011)
A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini (2011)

Beyond NWA



@ LHC 7 TeV

- The size of NLO QCD corrections to the differential distributions at the LHC
- For a fixed scale m_t at LHC the NLO QCD corrections are always positive and large at the level of $50\% - 60\%$

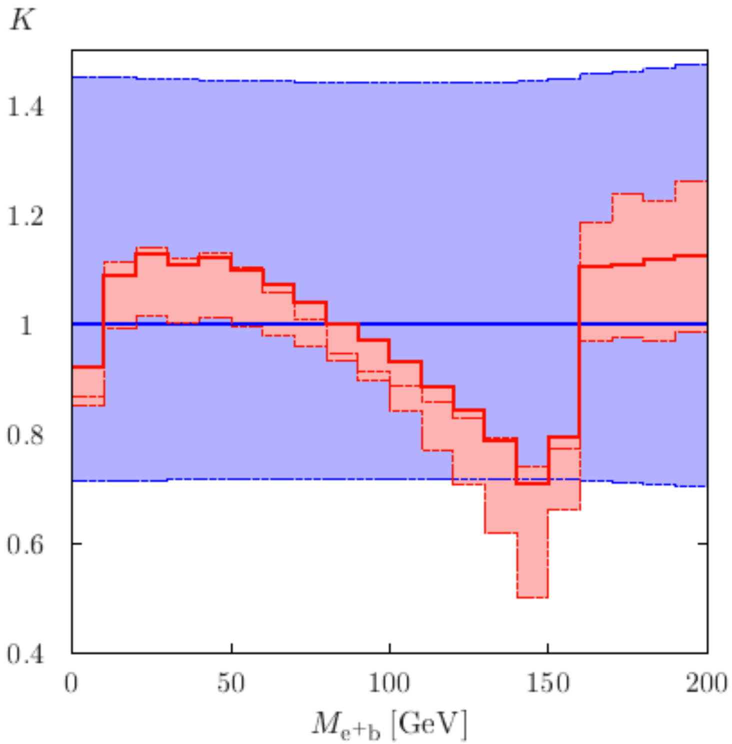
$pp \rightarrow l\nu\ l\nu\ bb + X$

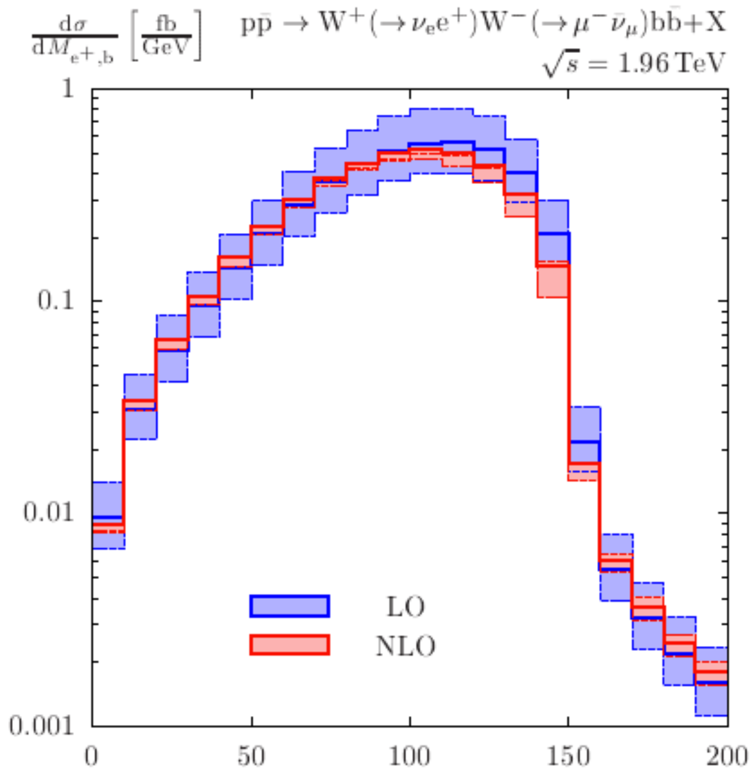
G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, M. Worek (2011)

Finite Width Corrections

@ TeVatron 1.96 TeV

- Invariant mass distribution m_{eb} at the Tevatron
- In NWA the LO has upper bound $m^2_{eb} \leq m^2_t - m^2_W \sim 150$ GeV
- NLO prediction is barely consistent with the LO uncertainty band close to the kinematic bound





A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini (2011)

A_{FB} for top anti-top

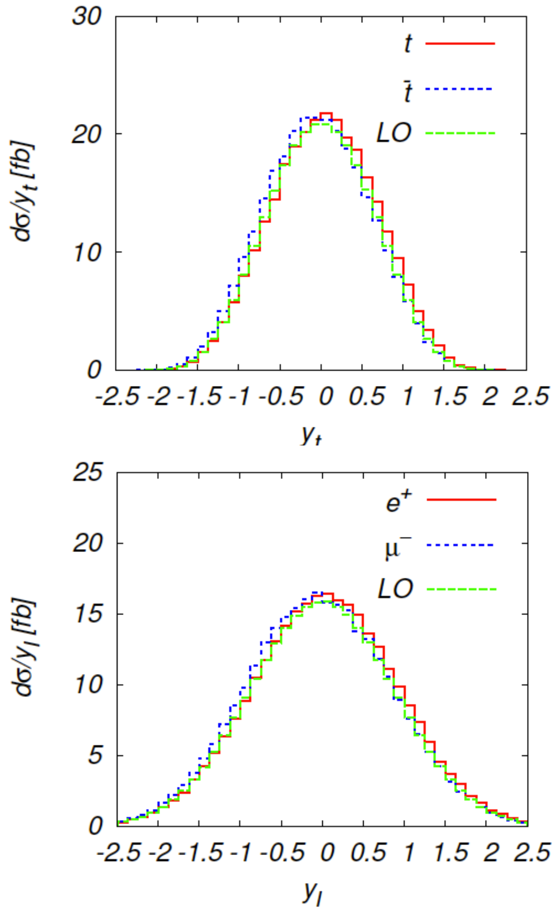
- Charge asymmetry and pair asymmetry of top quarks and leptonic charge asymmetry and lepton pair asymmetry for di-leptonic final state at the TeVatron with and without spin correlations

$$\mathcal{A}^{t} = \mathcal{A}^{t}_{FB} = -\mathcal{A}^{\bar{t}}_{FB}$$

$$\mathcal{A}^{\ell^+} = \mathcal{A}^{\ell^+}_{FB} = -\mathcal{A}^{\ell^-}_{FB}$$

@ TeVatron 1.96 TeV

	Tevatron (($t\bar{t}$ correlated))			Tevatron ($t\bar{t}$ uncorrelated))		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m_t	$2m_t$
A (NLO')	0.053	0.048	0.044	0.053	0.047	0.043
A (NLOW')	0.054	0.049	0.046	0.054	0.049	0.046
$A^{t\bar{t}}$ (NLO')	0.074	0.068	0.062	0.075	0.067	0.061
A^{tt} (NLOW')	0.078	0.071	0.066	0.077	0.070	0.065
A^{ℓ} (NLO')	0.038	0.033	0.031	0.037	0.033	0.030
A^{ℓ} (NLOW')	0.039	0.034	0.032	0.038	0.035	0.032
$A^{\ell\ell}$ (NLO')	0.047	0.042	0.038	0.050	0.045	0.041
$A^{\ell\ell}$ (NLOW')	0.048	0.044	0.040	0.052	0.047	0.043



W. Bernreuther, Z. G. Si (2010)
G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, M. Worek (2011)

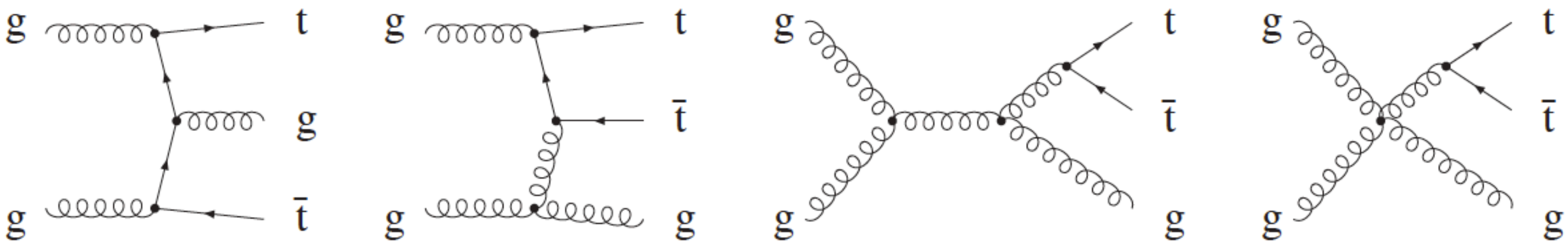
top anti-top + jet @ NLO

- Substantial number of events in the inclusive top-quark sample is accompanied by the additional jet
- Top quarks are produced with larger energies and p_T at the LHC
- Higher probability for top to radiate gluons
- Ratio of $\sigma_{tt+j} / \sigma_{tt}$ @ NLO

  - At the TeVatron: 30% and 11% for p_T cut of 20 GeV and 40 GeV

  - At the LHC: 47% and 22% for p_T cut of 50 GeV and 100 GeV

- Important background to various new physics searches
- Example: Higgs boson production via vector-boson fusion
- Need for precise theoretical predictions for this process



top anti-top + jet @ NLO

- Complete phenomenological studies at NLO QCD
  - On shell production

S. Dittmaier, P. Uwer, S. Weinzierl (2007) (2009)

  - NLO corrections to the production with LO decays in NWA
  - NLO corrections to the production and decays (with radiative one) in NWA
  - $pp \rightarrow ttj + X \rightarrow WWbbj + X \rightarrow l\nu\ l\nu\ bbj + X$
  - $pp \rightarrow ttj + X \rightarrow WWbbj + X \rightarrow l\nu\ jj\ bbj + X$

K. Melnikov, M. Schulze (2010)
K. Melnikov, A. Scharf, M. Schulze (2012)

- First results of NLO+PS matching for top anti-top plus jet
  - leading soft and collinear logarithms are resumed
  - exclusive, hadron level events can be generated
- Two calculations based on the POWHEG BOX method

A. Kardos, C. G. Papadopoulos, Z. Trocsanyi (2011)
S. Alioli, S. Moch, P. Uwer (2012)

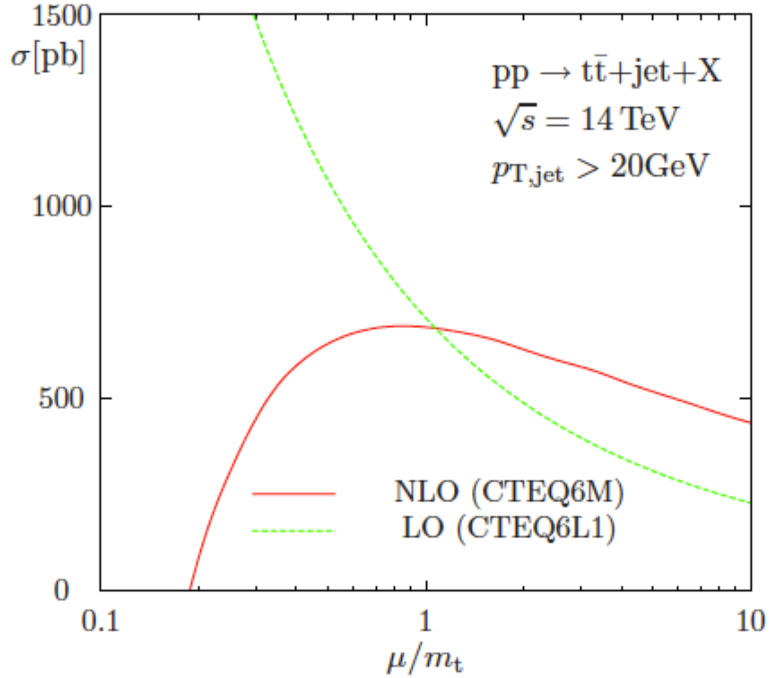
top quarks on-shell

	$\sigma_{t\bar{t}\text{jet}}$[pb]	
$p_{\text{T,jet,cut}}$ [GeV]	LO	NLO
20	$710.8(8)^{+358}_{-221}$	$692(3)3^{-40}_{-62}$
50	$326.6(4)^{+168}_{-103}$	$376.2(6)^{+17}_{-48}$
100	$146.7(2)^{+77}_{-47}$	$175.0(2)^{+10}_{-24}$
200	$46.67(6)^{+26}_{-15}$	$52.81(8)^{+0.8}_{-6.7}$

NLO QCD Corrections
K = NLO/LO = **1.15**

Scale dependence
LO **51%** → NLO **12%**

@ LHC 14 TeV



- Scale dependence of the LO and NLO cross sections at the LHC
- Integrated cross sections for different values of p_T(jet) cut

S. Dittmaier, P. Uwer, S. Weinzierl (2007)

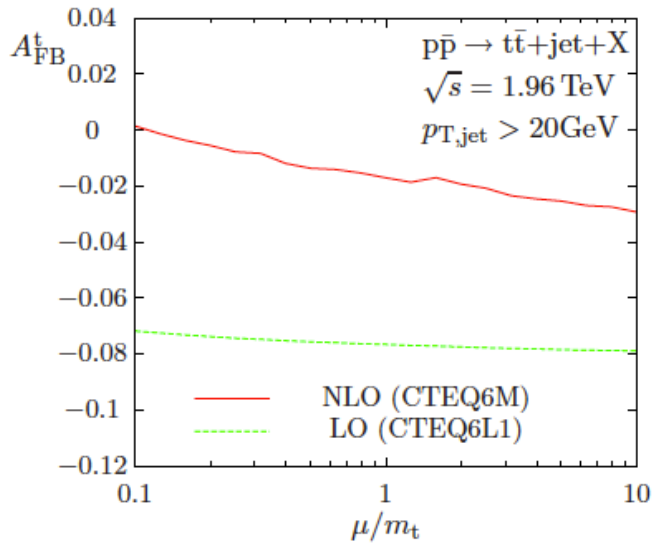
A_{FB} for top anti-top plus jet

@ TeVatron 1.96 TeV

- Forward–backward charge asymmetry at the Tevatron for different values of p_T(jet) cut

$p_{T,\text{jet,cut}}$ [GeV]	A^t_{FB} [%] LO	A^t_{FB} [%] NLO
20	$-7.69(4)^{+0.10}_{-0.085}$	$-1.77(5)^{+0.58}_{-0.30}$
30	$-8.29(5)^{+0.12}_{-0.085}$	$-2.27(4)^{+0.31}_{-0.51}$
40	$-8.72(5)^{+0.13}_{-0.10}$	$-2.73(4)^{+0.35}_{-0.49}$
50	$-8.96(5)^{+0.14}_{-0.11}$	$-3.05(4)^{+0.49}_{-0.39}$

- Scale dependence of the LO and NLO forward–backward charge asymmetry of the top quark



$$\mathcal{A}^t_{FB,LO} = \frac{\sigma_{LO}(y_t > 0) - \sigma_{LO}(y_t < 0)}{\sigma_{LO}(y_t > 0) + \sigma_{LO}(y_t < 0)}$$

$$\mathcal{A}^t_{FB,NLO} = \frac{\sigma^-_{LO} + \delta\sigma^-_{NLO}}{\sigma^+_{LO} + \delta\sigma^+_{NLO}}$$

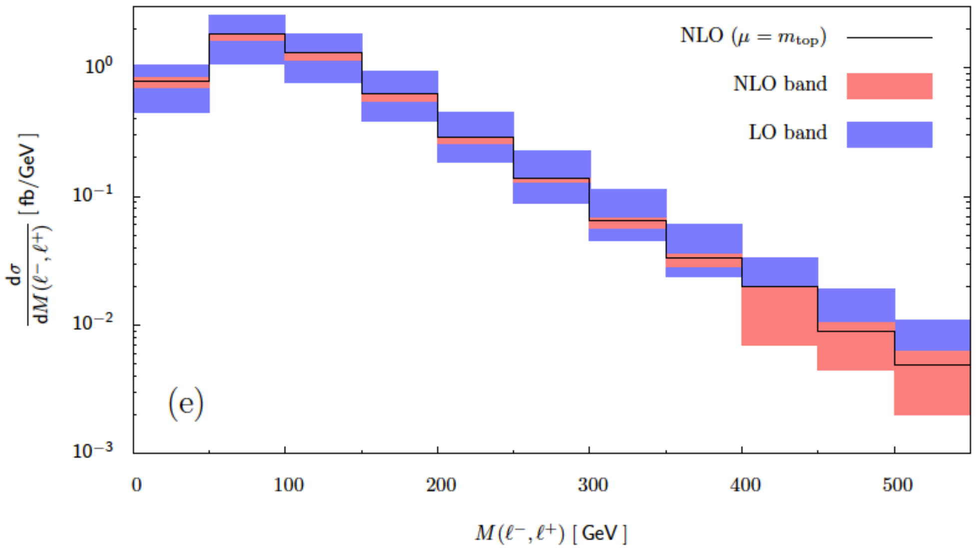
$$\mathcal{A}^t_{FB,NLO} = \frac{\sigma^-_{LO}}{\sigma^+_{LO}} \left(1 + \frac{\delta\sigma^-_{NLO}}{\sigma^-_{LO}} - \frac{\delta\sigma^+_{NLO}}{\sigma^+_{LO}}\right)$$

- Asymmetry at NLO via a consistent expansion in α_s

S. Dittmaier, P. Uwer, S. Weinzierl (2007) (2008)

ttj in NWA with LO decays

pp → ttj + X → WWbbj +X → lν lν bbj + X



- ❑ Invariant mass of two leptons
- ❑ Transverse momentum of lepton

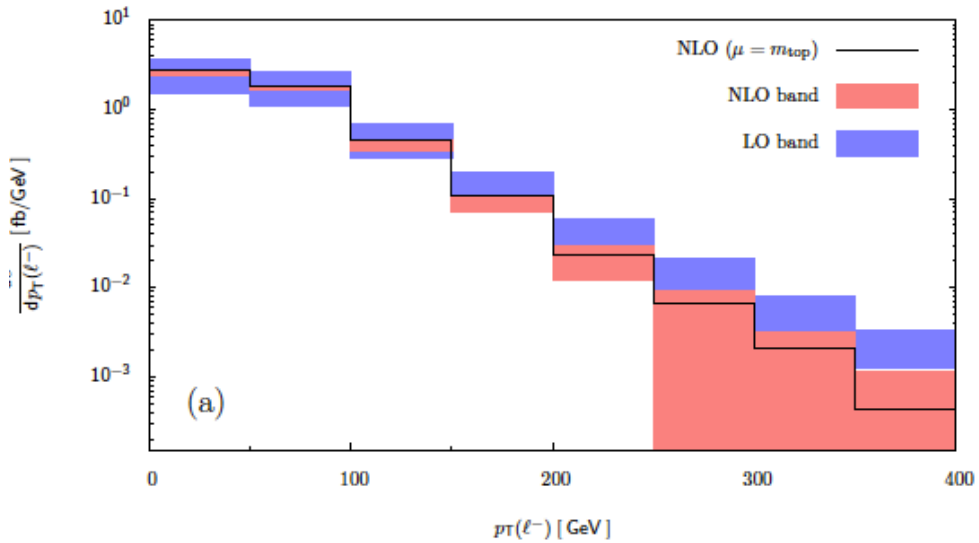
NLO QCD Corrections
K = NLO/LO = **1.12**

Scale dependence
LO **58%** → NLO **10%**

@ LHC 7 TeV

$$\sigma_{\rm LO} = 229.9^{+133.7}_{-78.2}\ {\rm fb}$$

$$\sigma_{\rm NLO} = 256.5^{-14.8}_{-25.6}\ {\rm fb}$$

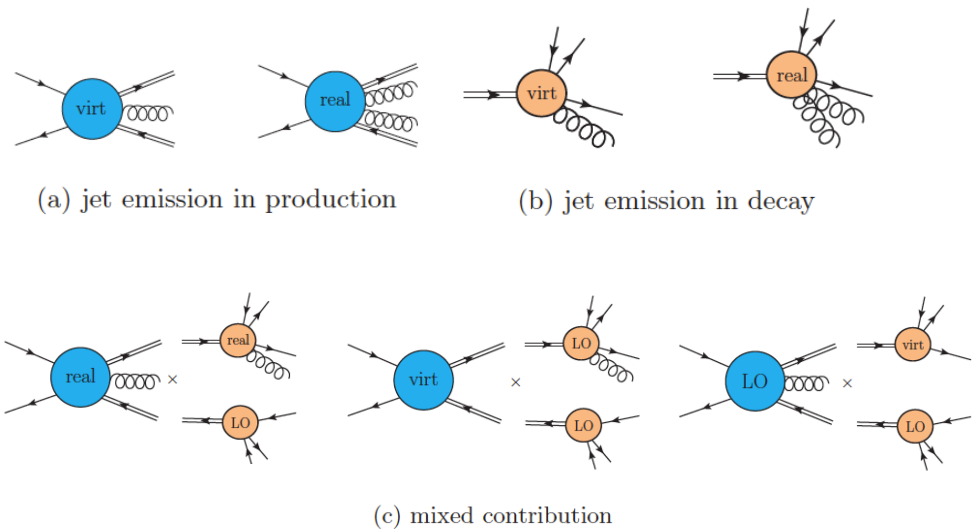


- ❑ For μ = m_t/2 negative distribution at high p_T (l) > 400 GeV
- ❑ Kinematic dependent scale (?)

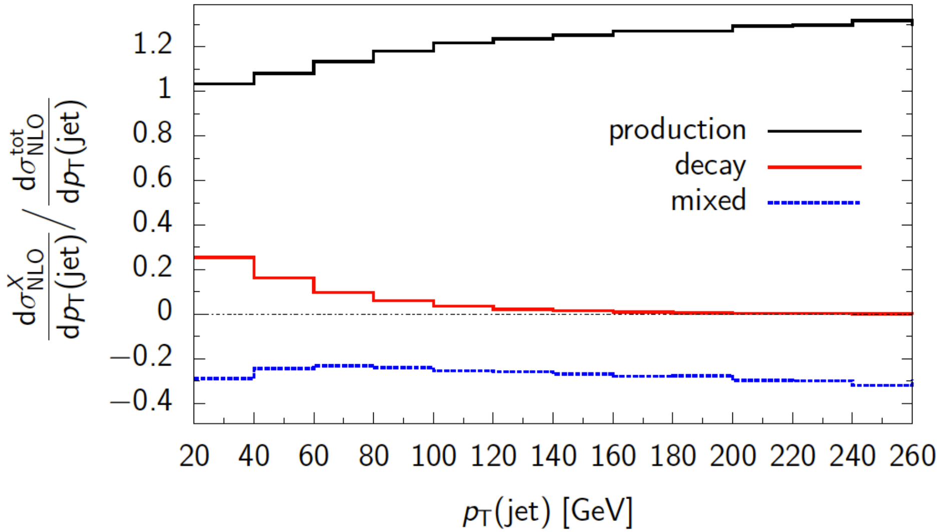
K. Melnikov, M. Schulze (2010)

ttj @ NLO in NWA

- ttj → WWbbj in NWA with top decays, including radiative decay (t → Wbj) described consistently at NLO QCD with spin correlations
- State of the art description of ttj process
- Radiation in the production dominates



@ LHC 7 TeV



$$\sigma_{\rm LO} = 316.9\,({\rm P}) + 33.4\,({\rm D}) = 350.3\,{\rm fb}$$

$$\sigma_{\rm NLO} = 323\,({\rm P}) + 40.5\,({\rm D}) - 75.5\,({\rm Mix}) = 288\,{\rm fb}$$

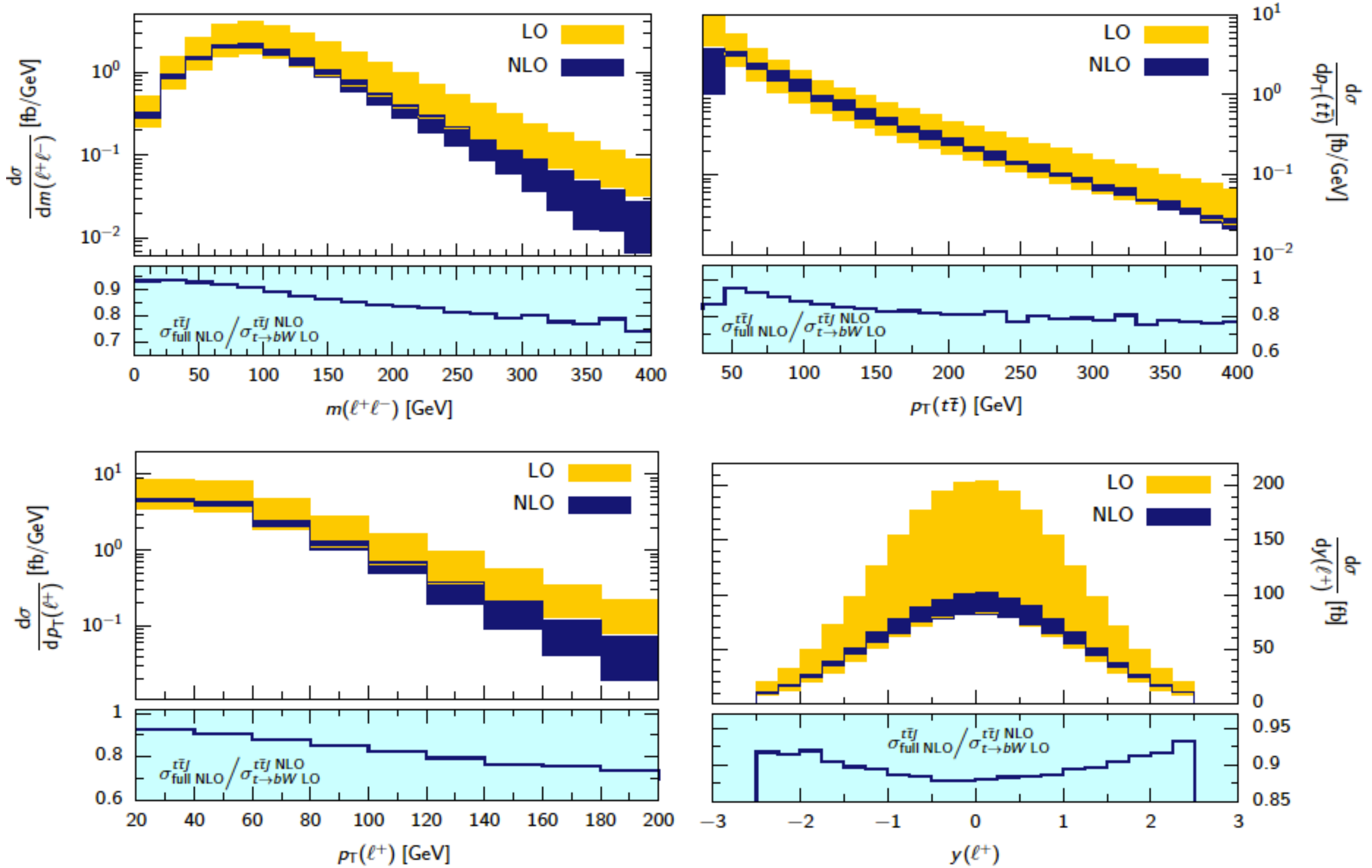
NLO QCD Corrections
K = NLO/LO = **0.82 (-18%)**

Scale dependence
LO **61%** → NLO **16%**

K. Melnikov, A. Scharf, M. Schulze (2012)

ttj @ NLO in NWA

@ LHC 7 TeV



K. Melnikov, A. Scharf, M. Schulze (2012)

top anti-top + 2j @ NLO

- Number of events in the inclusive tt sample accompanied by two additional jets
- Ratio of σ_{tt+j} / σ_{tt} @ NLO

  - At the TeVatron: 4% and 1% for p_T cut of 20 GeV and 40 GeV

  - At the LHC: 6% and 1% for p_T cut of 50 GeV and 100 GeV

- Important background for Higgs boson searches: ttjj and ttbb
- H → WW* produced via weak boson fusion (m_H ~ 130 GeV)
  - Higgs boson mass peak cannot be directly reconstructed
- H → bb produced via associated production with a top anti-top (m_H < 140 GeV)
  - Reconstruction of the H → bb mass peak difficult
  - The bb pair can be chosen incorrectly
  - b-tagging efficiency, two b-jets can arise from mistagged light jets

Very precise knowledge of QCD backgrounds is necessary !

top anti-top + 2j @ NLO

- Complete phenomenological studies at NLO QCD with on shell top quarks
  - ttbb at the LHC completed by two groups with per-mille agreement

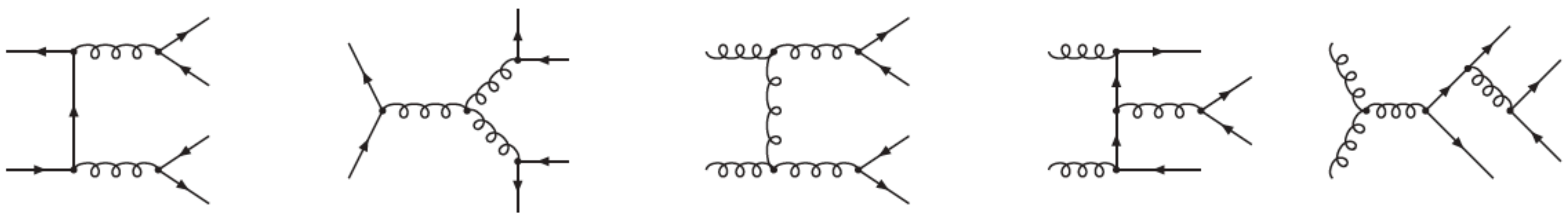
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini (2008) (2009) (2010)
G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek (2009)

  - ttbb also completed for the Tevatron

M. Worek (2012)

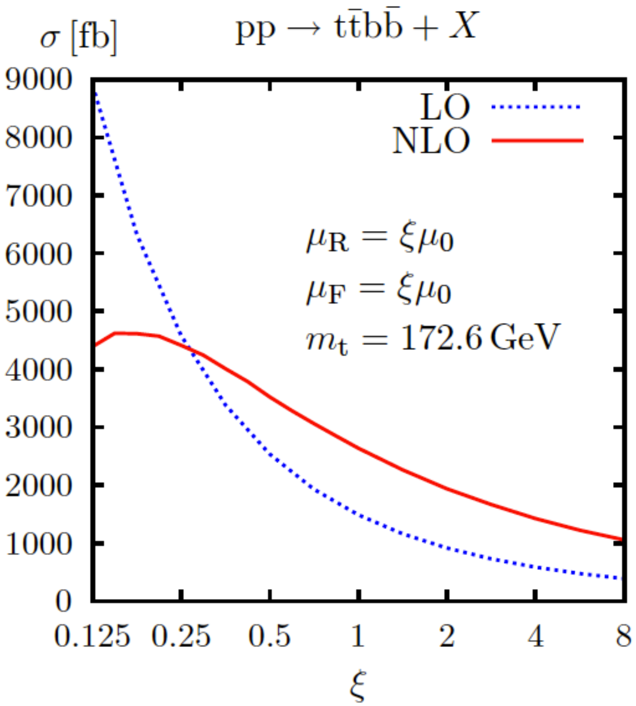
  - ttjj calculation both for the TeVatron and the LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek (2010) (2011)



ttbb @ NLO – top on shell

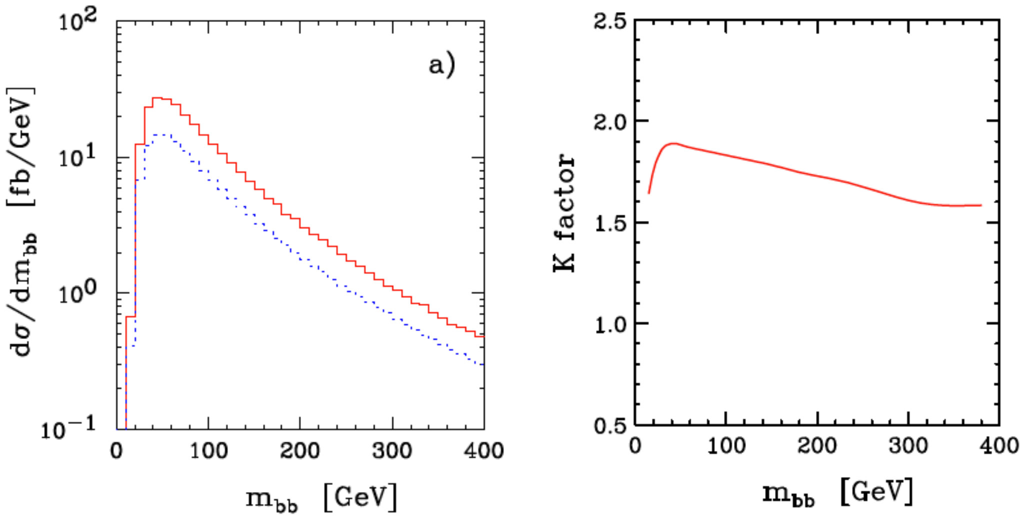
@ LHC 14 TeV



NLO QCD Corrections
K = NLO/LO = **1.77**

Scale dependence
LO **70%** → NLO **33%**

- ❑ Scale dependence for fixed scale m_t
- ❑ Invariant mass distribution of two b jets



$$\sigma^{LO}_{t\bar{t}b\bar{b}} = 1489.2 \begin{array}{l} +1036.8\ (70\%) \\ -\ \ 565.8\ (38\%) \end{array} \text{fb}$$

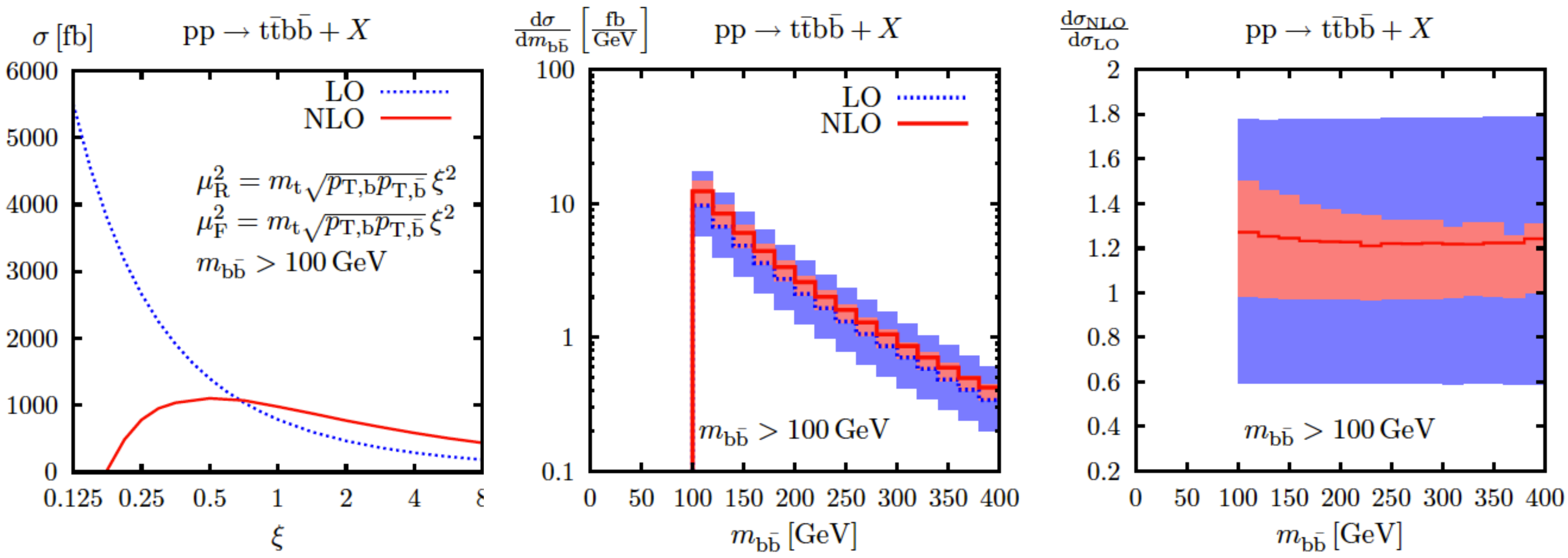
$$\sigma^{NLO}_{t\bar{t}b\bar{b}} = 2636 \begin{array}{l} +862\ (33\%) \\ -703\ (27\%) \end{array} \text{fb}$$

A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini (2009)
G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek (2009)

ttbb @ NLO – top on shell

@ LHC 14 TeV

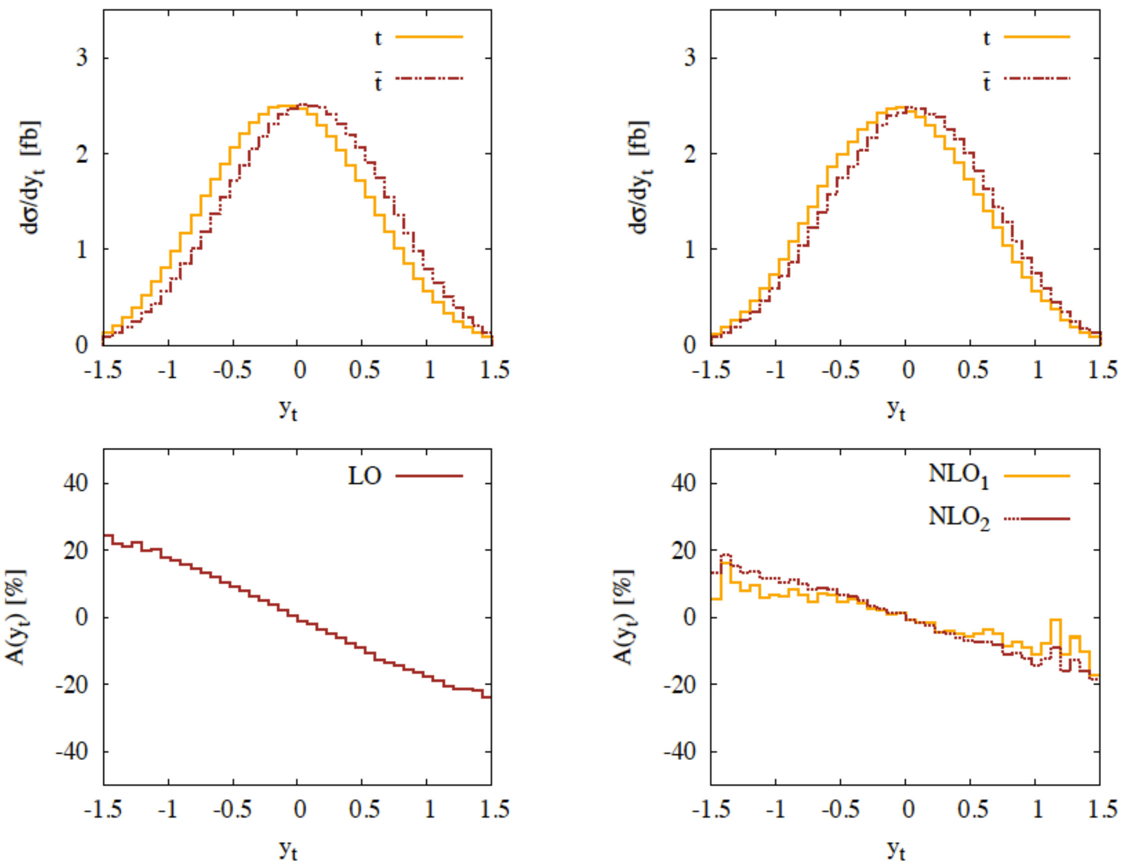
Setup	$m_{b\bar{b},\mathrm{cut}}$	$p_{\mathrm{T},b\bar{b},\mathrm{cut}}$	$p_{\mathrm{jet,veto}}$	$p_{\mathrm{T,b,cut}}$	$y_{\mathrm{b,cut}}$	σ_{LO} [fb]	σ_{NLO} [fb]	K
I	100	-	-	20	2.5	$786.3(2)^{+78\%}_{-41\%}$	$978(3)^{+13\%}_{-21\%}$	1.24
II	-	200	-	20	2.5	$451.8(2)^{+79\%}_{-41\%}$	$592(4)^{+13\%}_{-22\%}$	1.31
III	100	-	100	20	2.5	$786.1(6)^{+78\%}_{-41\%}$	$700(3)^{+0.4\%}_{-19\%}$	0.89
IV	100	-	-	50	2.5	$419.4(1)^{+77\%}_{-40\%}$	$526(2)^{+13\%}_{-21\%}$	1.25



A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini (2010)

A_{FB} for ttbb

- Rapidity distributions of the top and anti-top
- Differential asymmetry $A(y_t)$ as a function of top quark rapidity



M. Worek (2012)

@ TeVatron 1.96 TeV

- Integrated forward-backward asymmetry of the top quark at LO and NLO

$$\mathcal{A}^{\mathbf{t}}_{\mathbf{FB,LO}} = -\mathbf{0.088(2)}$$

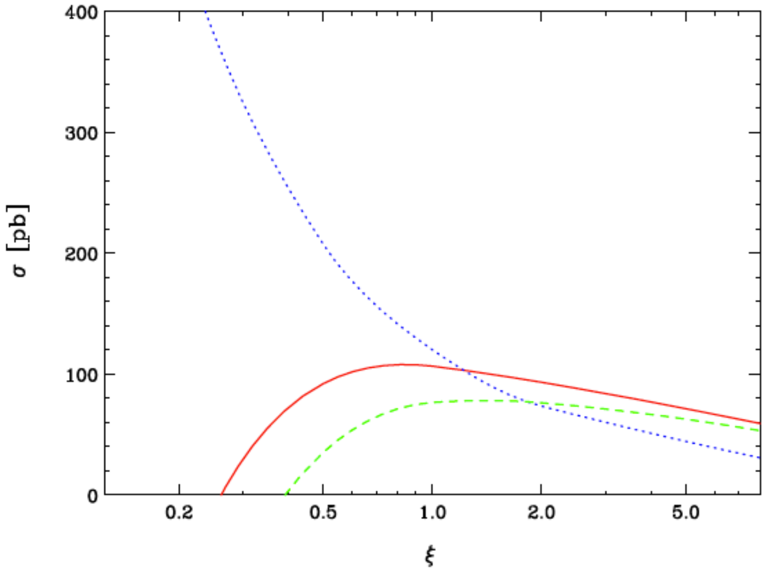
$$\mathcal{A}^{\mathbf{t}}_{\mathbf{FB,NLO}} = -\mathbf{0.044(6)}$$

- For an unexpanded ratio of the NLO cross sections

$$\mathcal{A}^{\mathbf{t}}_{\mathbf{FB,NLO}} = -\mathbf{0.061(14)}$$

ttjj @ NLO – top on shell

@ LHC 14 TeV



Process	$\sigma^{\rm LO}$ [pb]	Contribution
$pp \to t\bar{t}jj$	120.17(8)	100 %
$qg \to t\bar{t}qg$	56.59(5)	47.1 %
$gg \to t\bar{t}gg$	52.70(6)	43.8 %
$qq' \to t\bar{t}qq', \;\; q\bar{q} \to t\bar{t}q'\bar{q}'$	7.475(8)	6.2 %
$gg \to t\bar{t}q\bar{q}$	1.981(3)	1.6 %
$q\bar{q} \to t\bar{t}gg$	1.429(1)	1.2 %

- Scale dependence of total cross section at LO and NLO as well as NLO with jet veto of 50 GeV

$$\sigma^{\rm NLO}_{pp\to t\bar{t}jj+X} = (106.94 \pm 0.17)\ {\rm pb}$$

$$\sigma^{\rm NLO}_{pp\to t\bar{t}jj+X}(p_{T,X} < 50\ {\rm GeV}) = (76.58 \pm 0.17)\ {\rm pb}$$

NLO QCD Corrections
K = NLO/LO = **0.89 (-11%)**

Scale dependence
LO **72%** → NLO **13%**

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek (2010)

ttjj @ NLO – top on shell

@ LHC 7 TeV

CUTS	σ_{LO} [pb]	$\sigma_{NLO}^{anti-k_T}$ [pb]	$\sigma_{NLO}^{k_T}$ [pb]	$\sigma_{NLO}^{C/A}$ [pb]
$p_{T_j} > 50$ GeV $\Delta R_{jj} > 1.0$ $\lvert y_j \rvert < 2.5$	11.561(4)	9.95(2)	10.06(2)	10.04(2)

$\Delta R_{jj} > 1$
NLO QCD Corrections
K = NLO/LO = **0.86 (-14%)**

CUTS	σ_{LO} [pb]	$\sigma_{NLO}^{anti-k_T}$ [pb]	$\sigma_{NLO}^{k_T}$ [pb]	$\sigma_{NLO}^{C/A}$ [pb]
$p_{T_j} > 50$ GeV $\Delta R_{jj} > 0.5$ $\lvert y_j \rvert < 2.5$	13.398(4)	9.82(2)	9.86(2)	9.86(2)

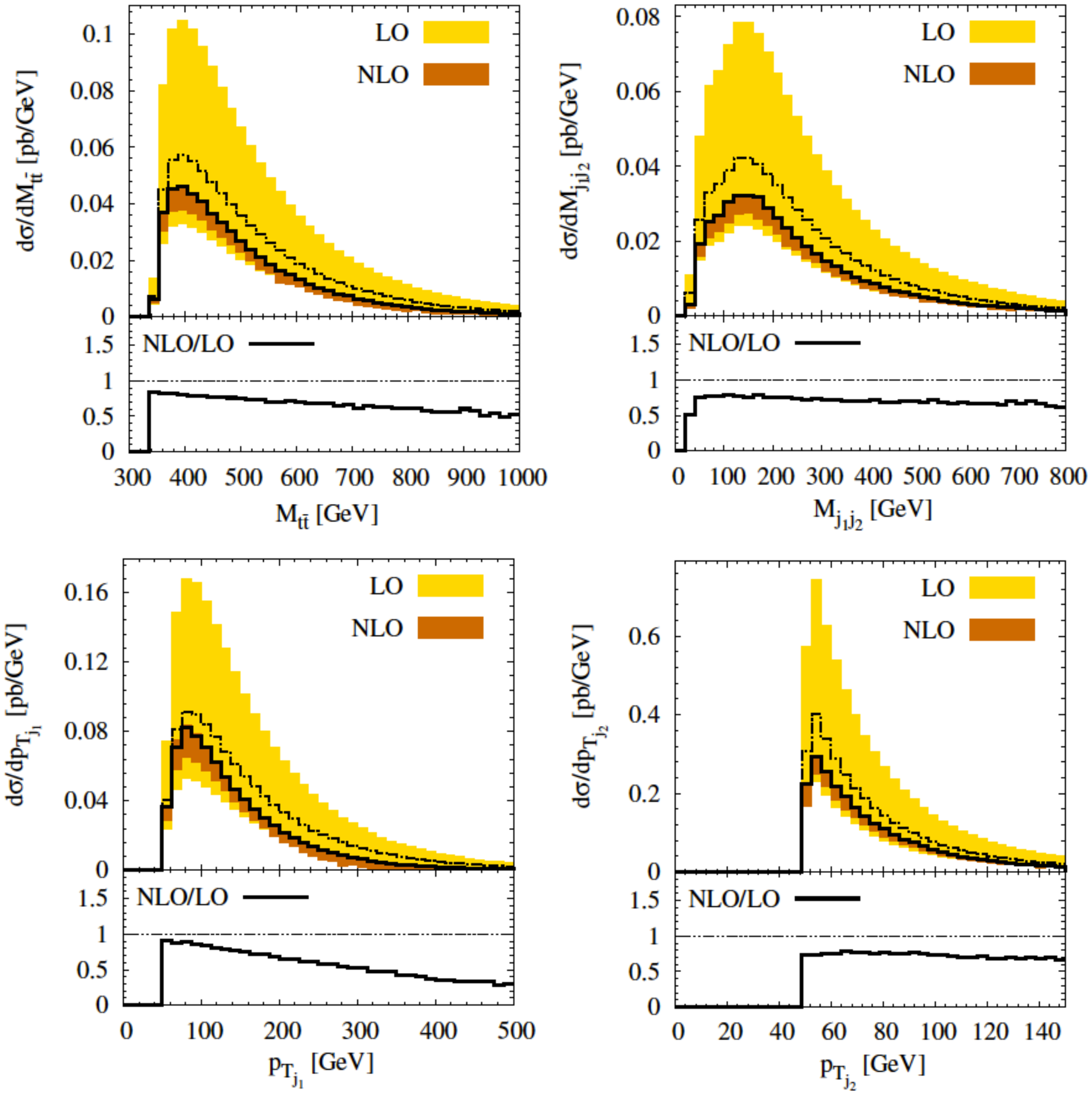
$\Delta R_{jj} > 0.5$
NLO QCD Corrections
K = NLO/LO = **0.73 (-27%)**

p_{T_j} CUT	σ_{LO} [pb]	$\sigma_{NLO}^{anti-k_T}$ [pb]	$\mathcal{K}$	[%]
$p_{T_j} > 50$ GeV	13.398(4)	9.82(2)	0.73	-27
$p_{T_j} > 75$ GeV	5.944(2)	4.115(8)	0.69	-31
$p_{T_j} > 100$ GeV	3.018(1)	1.944(4)	0.64	-36
$p_{T_j} > 125$ GeV	1.665(1)	0.993(2)	0.60	-40

- Within 50 -100 GeV range corrections are quite stable
- K-factor changed by 9%

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek (2011)

ttjj @ NLO – top on shell



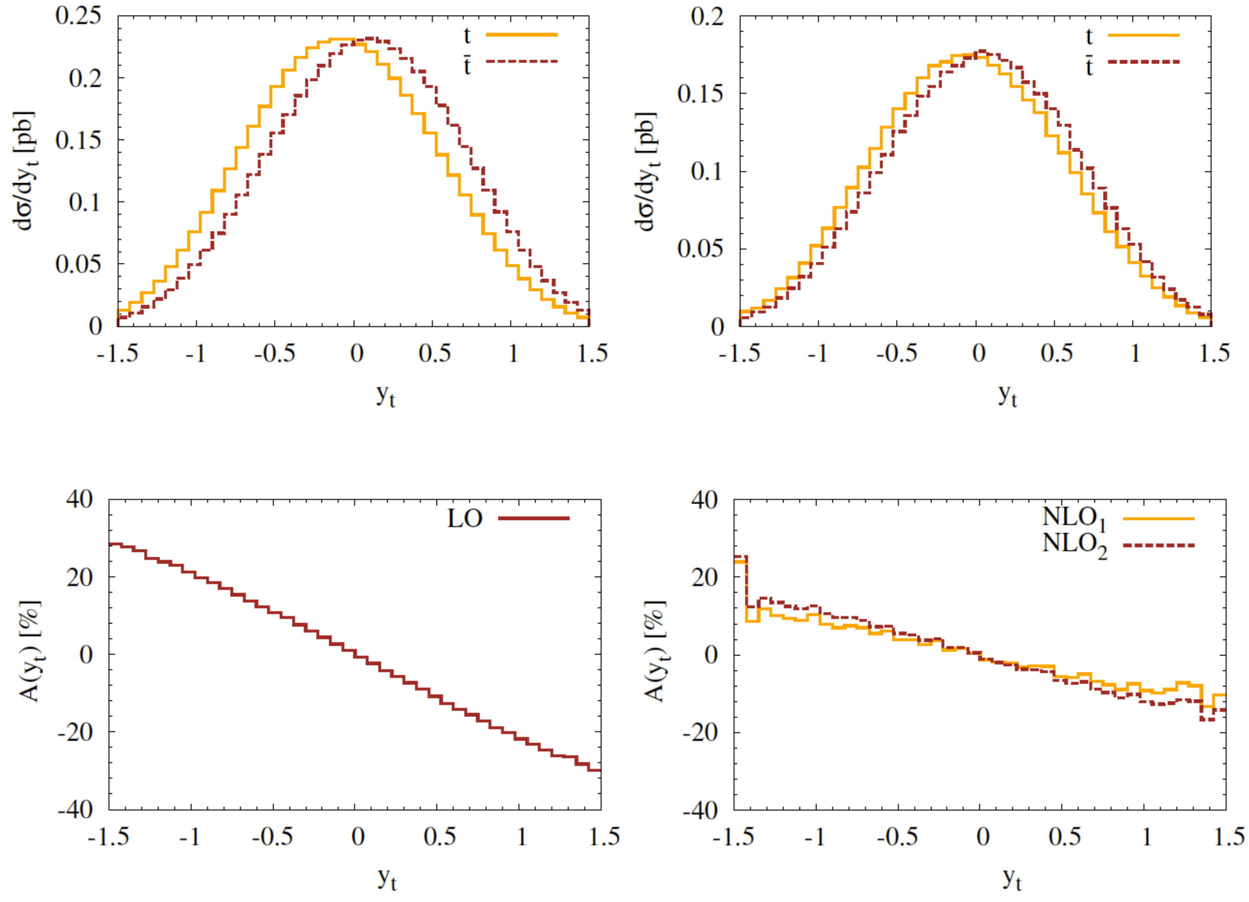
@ LHC 7 TeV

- NLO QCD corrections to the distributions are negative
- Analysis done for fixed scale
- If large distortions improvement can be achieved via dynamical scale
- Invariant dijet mass do not show major distortions

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek (2011)

A_{FB} for ttjj

- Rapidity distribution of top and anti-top at LO and NLO
- Differential charge asymmetry $A(y_t)$ as a function of top rapidity



@ TeVatron 1.96 TeV

- Integrated A_{FB} of the top quark at LO and NLO

$$\mathcal{A}^{\mathbf{t}}_{\mathbf{FB,LO}} = \mathbf{-0.103(4)}$$

$$\mathcal{A}^{\mathbf{t}}_{\mathbf{FB,NLO}} = \mathbf{-0.046(6)}$$

- For an unexpanded ratio of the NLO cross sections

$$\mathcal{A}^{\mathbf{t}}_{\mathbf{FB,NLO}} = \mathbf{-0.058(42)}$$

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek (2011)

Summary

NLO Status	On-shell	NWA	Full	Parton Shower
tt	YES	YES	YES	YES
ttj	YES	YES	NO	YES
ttjj	YES	NO	NO	NO
ttbb	YES	NO	NO	NO

Summary & Outlook

- New problem at the LHC, multiparticle final states !
- Hard emission is less suppressed at LHC energies
- Remarkable development in NLO calculations driven by the LHC needs
- $2 \rightarrow 4$ processes currently scrutinized
- $2 \rightarrow 5$ and maybe $2 \rightarrow 6$ processes doable with new methods
- Cannot do better than LO for $2 \rightarrow 7(8)$ processes

- Better understanding of the scale choice that describes high p_T region correctly
- Dynamic scales that depend on the event structure

- **Goal:** Fully realistic final state such as WWbbX with X = j, jj, H, Z, A, γ
  for the LHC matched to parton shower with higher than LL accuracy

- Meanwhile huge progress in the resummation and NNLO calculations for top
- First NNLO calculation for $2 \rightarrow 2$ process at hadron collider is now available !
- $\mathbf{q\bar{q} \rightarrow t\bar{t} + X}$ @ TeVatron calculated !

P. Bärnreuther, M. Czakon, A. Mitov
Rencontres de Moriond
QCD and High Energy Interactions (2012)