Differential Top Pair Cross Section And Top Anti-Top + Jets Physics

Malgorzata Worek
Wuppertal University

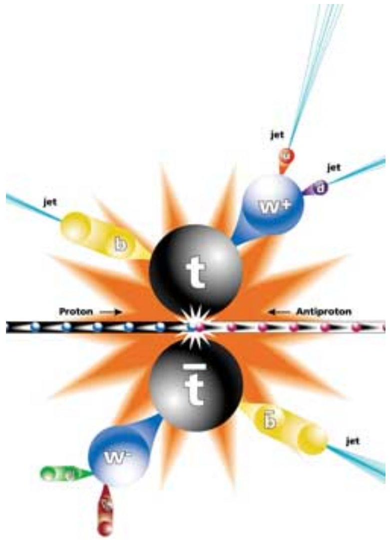
5th International Workshop on Top Quark Physics, 16 – 21 September 2012, Winchester UK

Motivations

- Successful running of collisions at 7 TeV and 8 TeV @ LHC with $\mathcal{L}$ = 10 fb^{-1}
- August 2012 Delivered: **$\mathcal{L}$ = 12.7 fb^{-1} at 8 TeV**
- The large statistics have opened a window on entirely new measurements & analysis of novel more complex final states
- Reducing theoretical uncertainties for correct interpretation of the data
- A theoretical accuracy at least at NLO is desirable & demanded for most analyses
    - More reliable theoretical error related to the scale dependence
    - Normalization and shape of distributions
    - Improved description of jets
    - Correct choice of scales for many scale processes: V+ jets, ttH, ttbb, …

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

Top Anti-Top Pairs



- Distinguished by its large mass, close to EWSB scale
- Potentially sensitive to physics beyond the Standard Model

  - Are there new particles lighter than the top quark ?
  - Does the top quark decay into them ?
  - Could non-SM physics manifest itself in non-standard couplings of top ?

- Copiously produced @ LHC in top anti-top pairs
- Production cross section, decays and properties can be studied with high precision
- Accurate measurements must be accompanied by precise calculations

- Precision m_t determinations
- tt backgrounds to new physics that are suppressed by vetoing top resonances
- Quantify the accuracy of the narrow-top-width approximation with only on-shell tt contributions that corresponds to $\Gamma_t \rightarrow 0$

Top Anti-Top Pairs

- 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

    Bernreuther, Brandenburg, Si, Uwer '04
  - Mixed QCD-EW Corrections *Bernreuther, Si '10*
  - Flexible Monte Carlo implementation, fully differential level

    Melnikov, Schulze '09
  - Independent implementation in MCFM

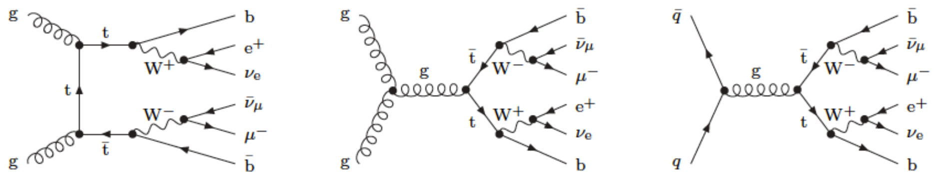
    Campbell, Ellis '12
- Results of NLO+PS matching available since quite some time
  - MC@NLO *Frixione, Nason, Webber '03*
  - POWHEG *Frixione, Nason, Ridolfi '07*

Beyond NWA

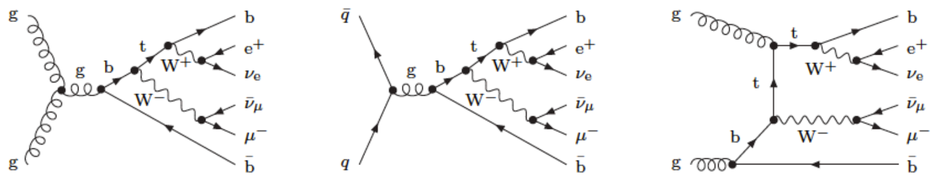
- Complete NLO description of the production of top anti-top pairs including interferences, off-shell effects, non-resonant backgrounds, spin correlations
- State of the art description of tt process
- Two independent calculations with per-mille agreement (di-lepton channel)
- Finite-width effects on σ_{tt} around 1% both at the Tevatron and the LHC

HELAC-NLO: Bevilacqua, Czakon, Hameren, Papadopoulos, Worek '11

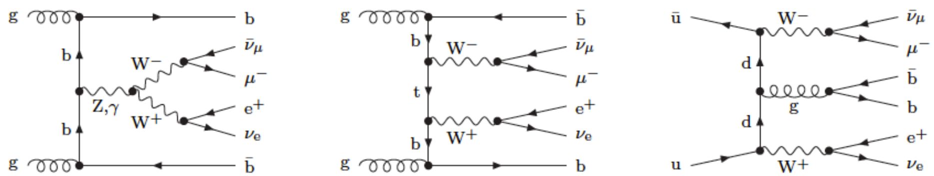
Denner, Dittmaier, S. Kallweit, Pozzorini '11 '12



two top-quark resonances



one top-quark resonance



no top-quark resonances

Top Anti-Top + Jet

- ❑ 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

Dittmaier, Uwer, Weinzierl '07 '09

- ❑ 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

- Complete phenomenological studies at NLO QCD
  - On shell production

Dittmaier, Uwer, Weinzierl '07 '09

  - Narrow-width approximation
  - NLO corrections to the production with LO decays of tops
  - NLO corrections to the production and decays (with radiative top decay)

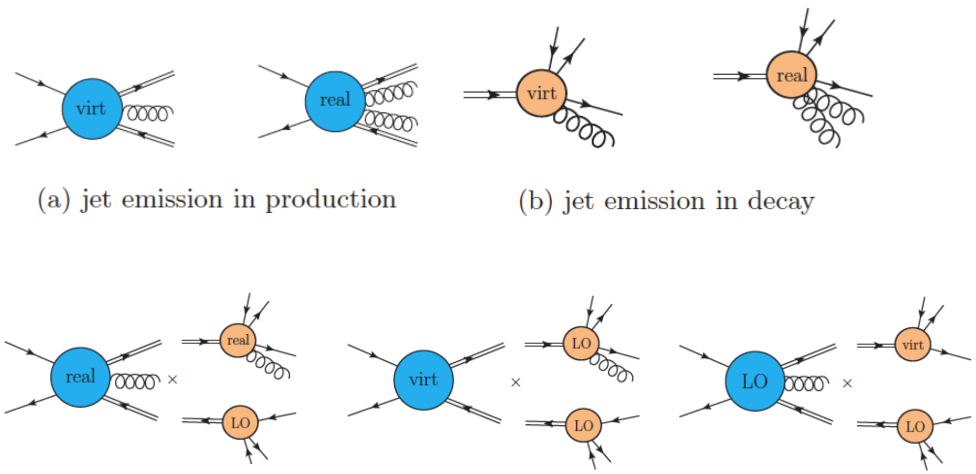
Melnikov, Schulze '10
Melnikov, Scharf, Schulze '12

- 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
  - no spin correlations or LO spin correlations

Kardos, Papadopoulos, Trocsanyi '11
Alioli, Moch, Uwer '12

Top Anti-Top + Jet

- Narrow-width approximation
- NLO QCD corrections and jet radiation in top quark decays t → Wbj
- Spin correlations @ NLO
- Radiation in the production dominates



(a) jet emission in production (b) jet emission in decay

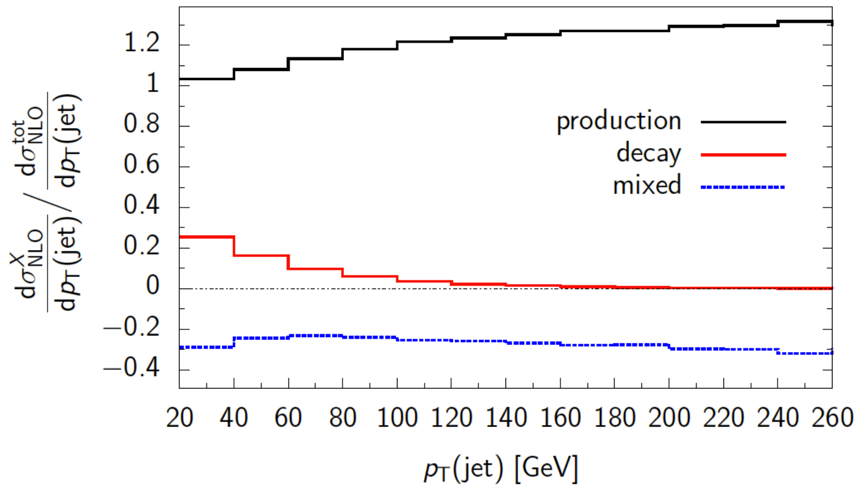
(c) mixed contribution

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

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

Melnikov, Scharf, Schulze '12

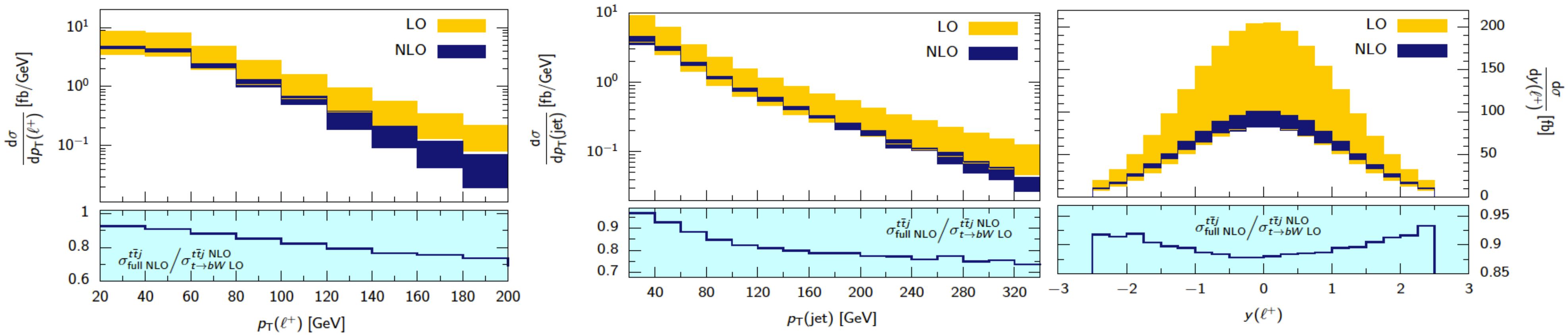
@ LHC 7 TeV



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

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

Top Anti-Top + Jet



- Hard jet emission in the production stage with LO decays are compared to full NLO results in lower panes
- QCD corrections and jet radiation in decays can lead to significant changes in shapes of distributions
- Fully consistent treatment of top quark pair production and decay in association with a jet at NLO in perturbative QCD

Melnikov, Scharf, Schulze '12

Top Anti-Top + 2 Jets

- Substantial number of events in the inclusive top quark sample is accompanied by the additional jet
- 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

Dittmaier, Uwer, Weinzierl '07 '09

- Number of events in the inclusive tt sample accompanied by two additional jets
- Ratio of $\sigma_{tt+jj} / \sigma_{tt}$ @ 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

HELAC-NLO: Bevilacqua, Czakon, Papadopoulos, Worek '10 '11

Top Anti-Top + 2 Jets

- Important background for Higgs searches @ Tevatron and @ LHC

- $H \to WW^*$ produced via weak boson fusion

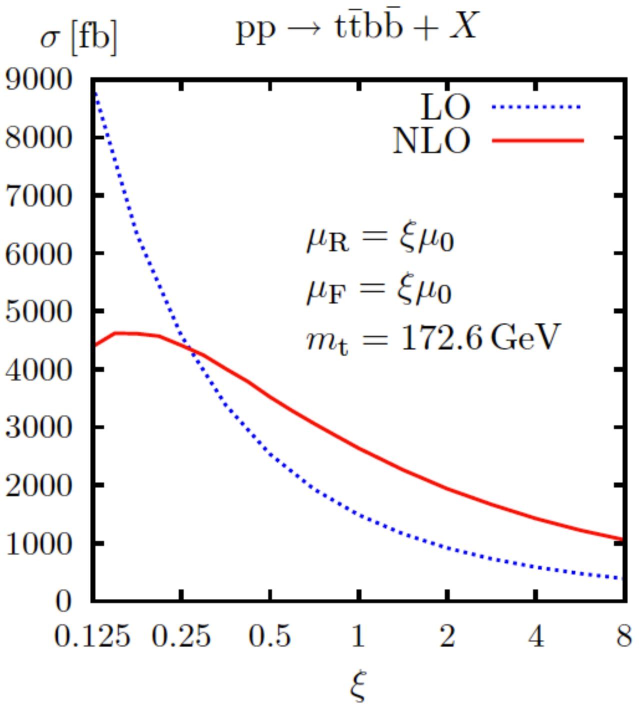
  - For $m_H \sim 130$ GeV, i.e. when $BR(H \to WW^*)$ is large enough
  - Higgs boson mass peak cannot be directly reconstructed
  - Background processes can not be measured from the side bands

- $H \to bb$ produced via associated production with a tt pair

  - Process useful only in the low mass range $m_H < 135$ GeV
  - Unique access to the top and bottom Yukawa couplings
  - Reconstruction of the $H \to bb$ mass peak difficult
  - The bb pair can be chosen incorrectly
  - b-tagging efficiency, two b-jets can arise from mistagged light jets

Top Anit-Top + 2b Jets

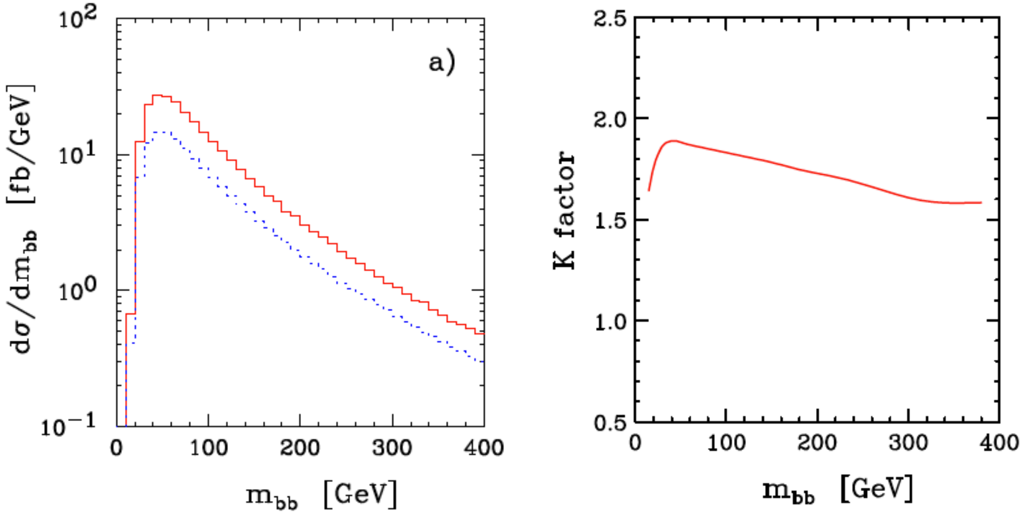
@ LHC 14 TeV



NLO QCD Corrections
K = NLO/LO = **1.77 (+77%)**

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

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



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

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

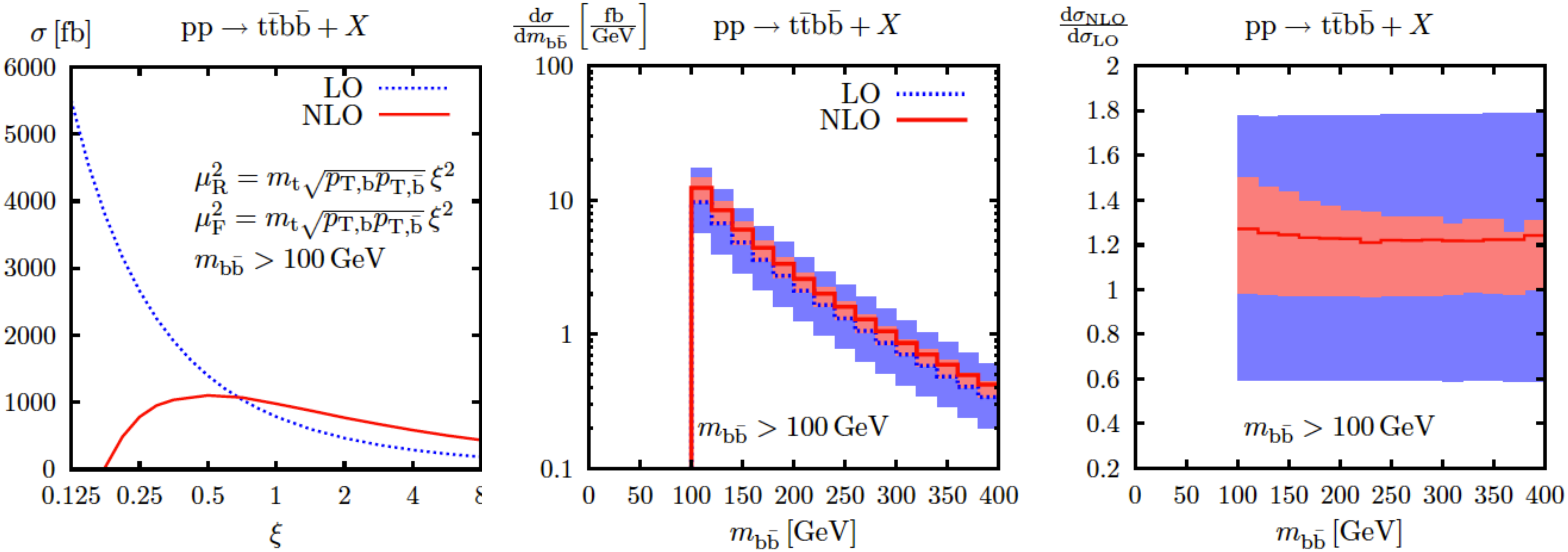
Bredenstein, Denner, Dittmaier, Pozzorini '08 '09 '10
HELAC-NLO: Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09
HELAC-NLO: Worek '12

Top Anit-Top + 2b Jets

@ LHC 14 TeV

Setup	$m_{\mathrm{b\bar{b}},\mathrm{cut}}$	$p_{\mathrm{T},\mathrm{b\bar{b}},\mathrm{cut}}$	$p_{\mathrm{jet},\mathrm{veto}}$	$p_{\mathrm{T},\mathrm{b},\mathrm{cut}}$	$y_{\mathrm{b},\mathrm{cut}}$	σ_{LO}	σ_{NLO}	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

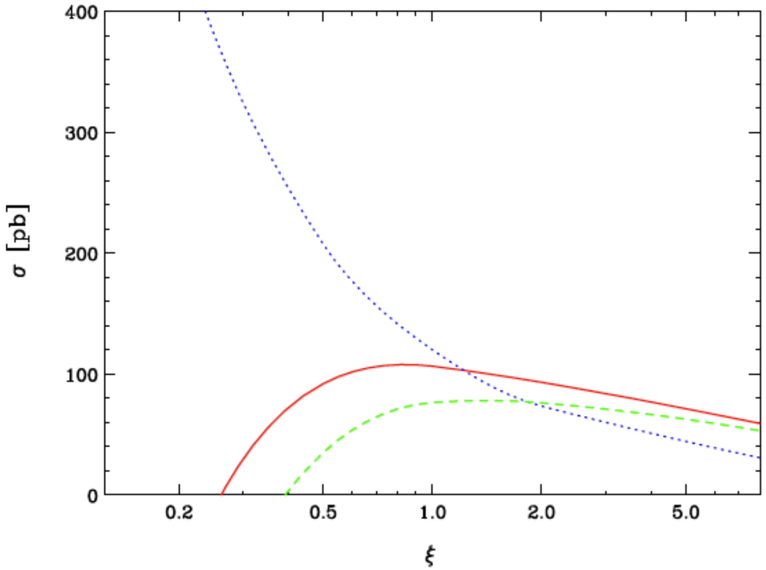
[fb]



Bredenstein, Denner, Dittmaier, Pozzorini '10

Top Anti-Top + 2 Jets

@ LHC 14 TeV



Process	σ^{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

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

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

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

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

HELAC-NLO: Bevilacqua, Czakon, Papadopoulos, Worek '10

Top Anti-Top + 2 Jets

@ LHC 7 TeV

Cuts	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}^{\rm anti-k_T}$ [pb]	$\sigma_{\rm NLO}^{\rm k_T}$ [pb]	$\sigma_{\rm NLO}^{\rm C/A}$ [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	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}^{\rm anti-k_T}$ [pb]	$\sigma_{\rm NLO}^{\rm k_T}$ [pb]	$\sigma_{\rm NLO}^{\rm C/A}$ [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)

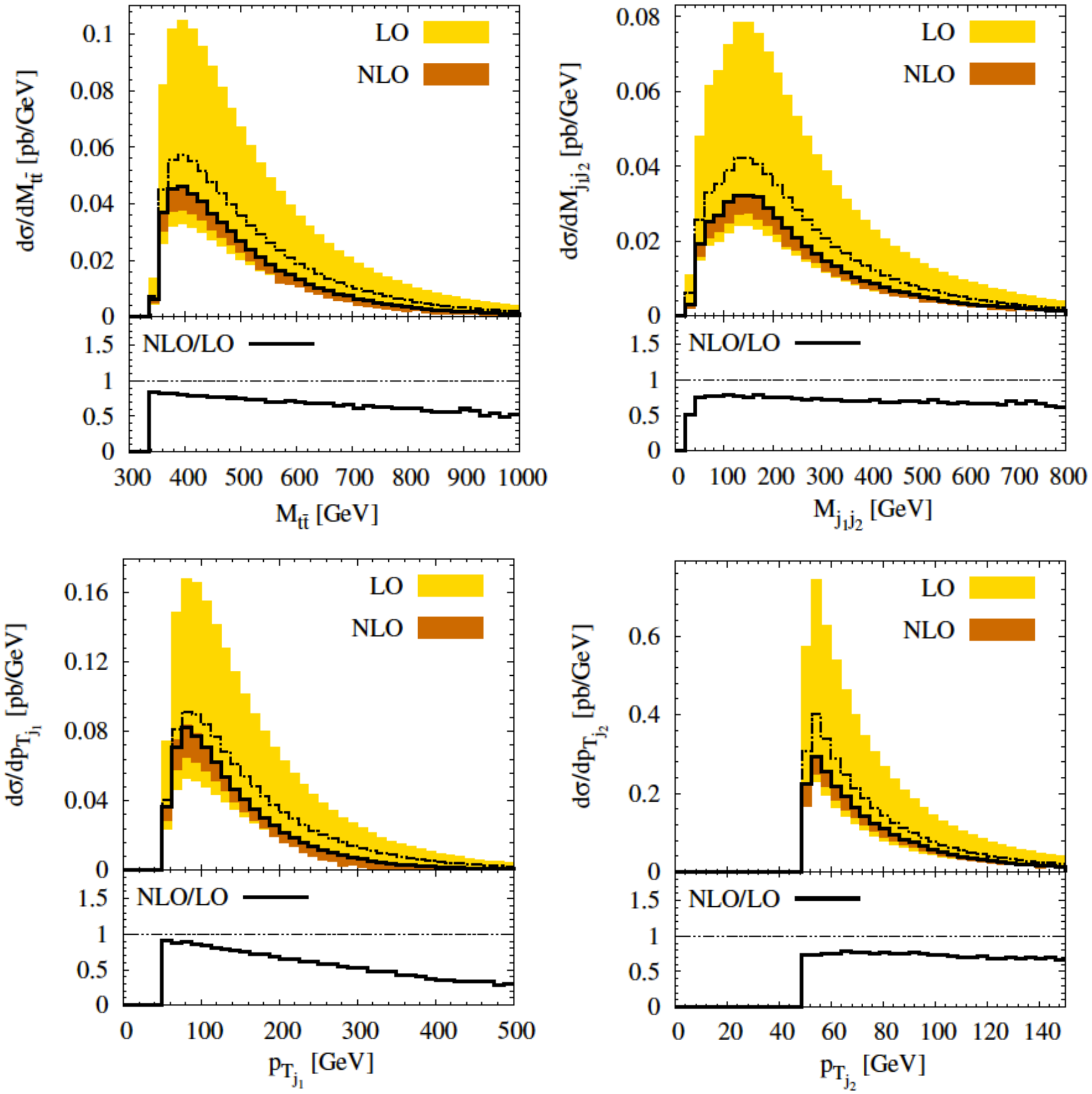
$\Delta R_{jj} > 0.5$
NLO QCD Corrections
K = NLO/LO = **0.73 (-27%)**

p_{T_j} Cut	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}^{\rm anti-k_T}$ [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%

HELAC-NLO: Bevilacqua, Czakon, Papadopoulos, Worek ‘10 ‘11

Top Anti-Top + 2 Jets



@ LHC 7 TeV

- NLO QCD corrections to the distributions are negative
- Up to 60% -70% in tails
- Analysis done for fixed scale
- Invariant di-jet mass do not show major distortions

HELAC-NLO: Bevilacqua, Czakon, Papadopoulos, Worek ‘10 ‘11

Four Tops

- LHC energy is sufficient to produce 4 tops at a sensible rate

- Interesting channel to probe several realizations of BSM Physics

  - Models of Higgs and top compositeness
  - Models involving the production of new colored resonances
  - Kaluza-Klein gluons from the Randall-Sudrum warped extra dimensions
  - Many models predict effective four-top quark interactions
  - New processes such as pp $\rightarrow$ GG and pp $\rightarrow$ ttG with G $\rightarrow$ tt
  - Major background for many processes arising from (…)MSSM
  - Heavy Higgs boson production
  - Long cascade decays of colored new particles like squarks or gluinos

Precise theoretical description of the four-top production rate in the Standard Model may help to constrain new physics scenarios

SCALE: $2m_T$ VS $H_T/4$

- Natural scale - the mass of the heavy particle appearing in the process
- Production relatively close to the threshold as defined by particle masses
- **14 TeV** and **MSTW2008 PDF** set

$\mu = 2m_t$

PROCESS	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=1}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=0.01}$ [fb]	K-FACTOR	[%]
$pp \to t\bar{t}t\bar{t} + X$	12.056(6)	15.33(2)	15.35(3)	1.27	27

$\mu = H_T/4$

PROCESS	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=1}$ [fb]	$\sigma_{\rm NLO}^{\alpha_{\max}=0.01}$ [fb]	K-FACTOR	[%]
$pp \to t\bar{t}t\bar{t} + X$	13.891(9)	16.87(2)	16.86(3)	1.21	21

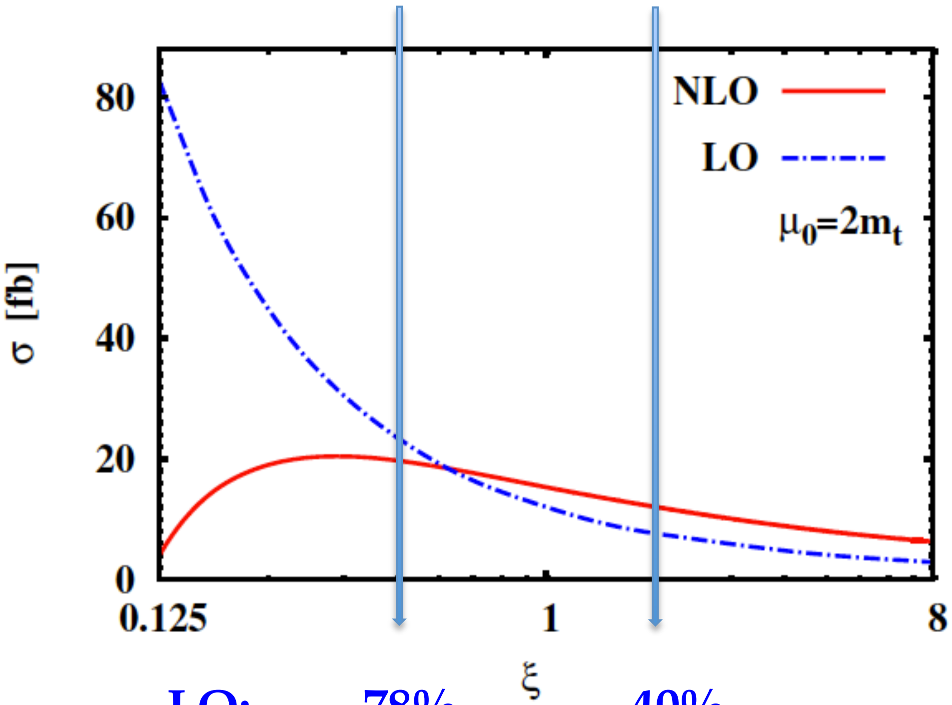
- Scale uncertainty at LO at the level of **78%** (**59%** after symmetrization)
- At NLO the scale uncertainty is reduced down to **26%**

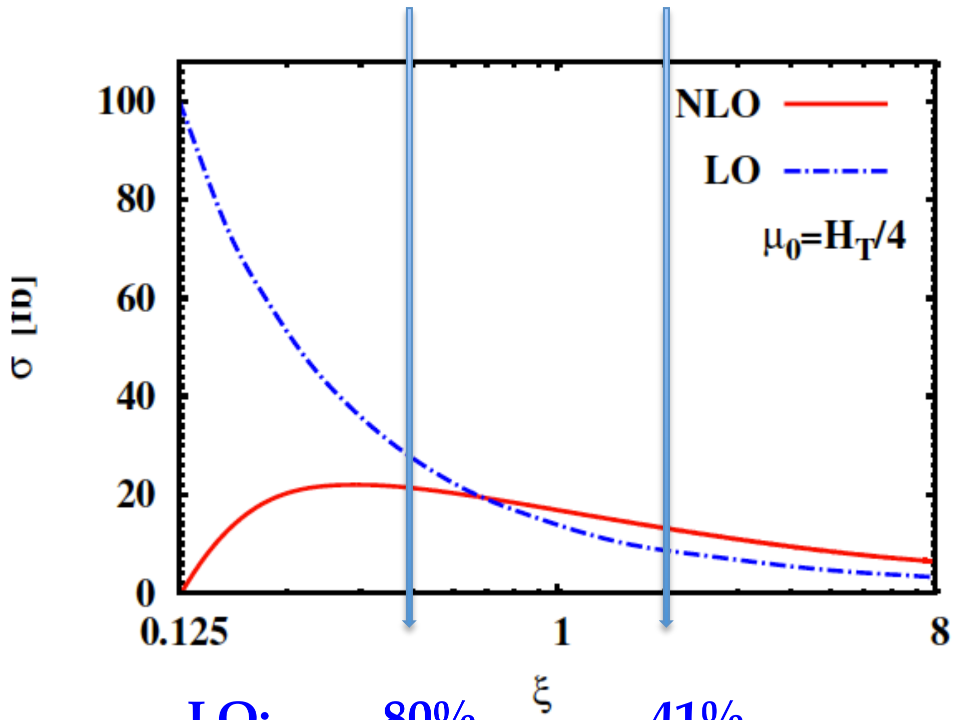
HELAC-NLO: Bevilacqua, Worek '12

Theoretical Uncertainty

- Scale dependence of the LO and NLO cross sections

HELAC-NLO: Bevilacqua, Worek '12





LO: 78% 40%

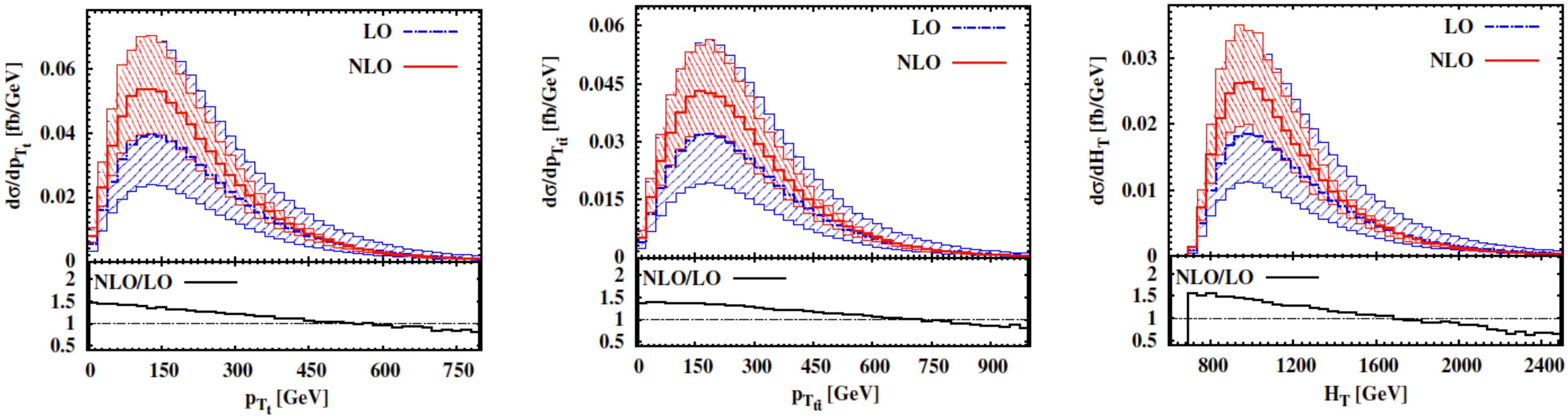
NLO: 26% 25%

LO: 80% 41%

NLO: 24% 25%

Differential Distributions

$\mu = 2m_t$

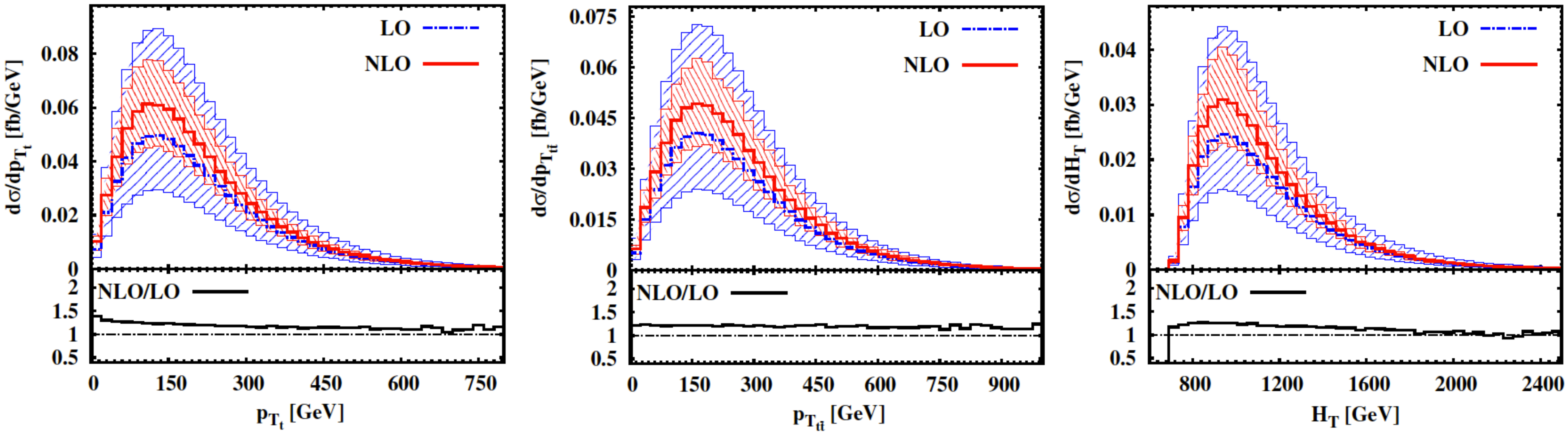


- Differential K factor
- Transverse momentum distribution of tt pair and of the top quark
- Distribution of the total transverse energy of the 4t system
- Distortions at the level of **60% - 80%**
- Large and negative NLO corrections affect the tails
- NLO error bands do not fit within the LO ones

HELAC-NLO: Bevilacqua, Worek '12

Differential Distributions

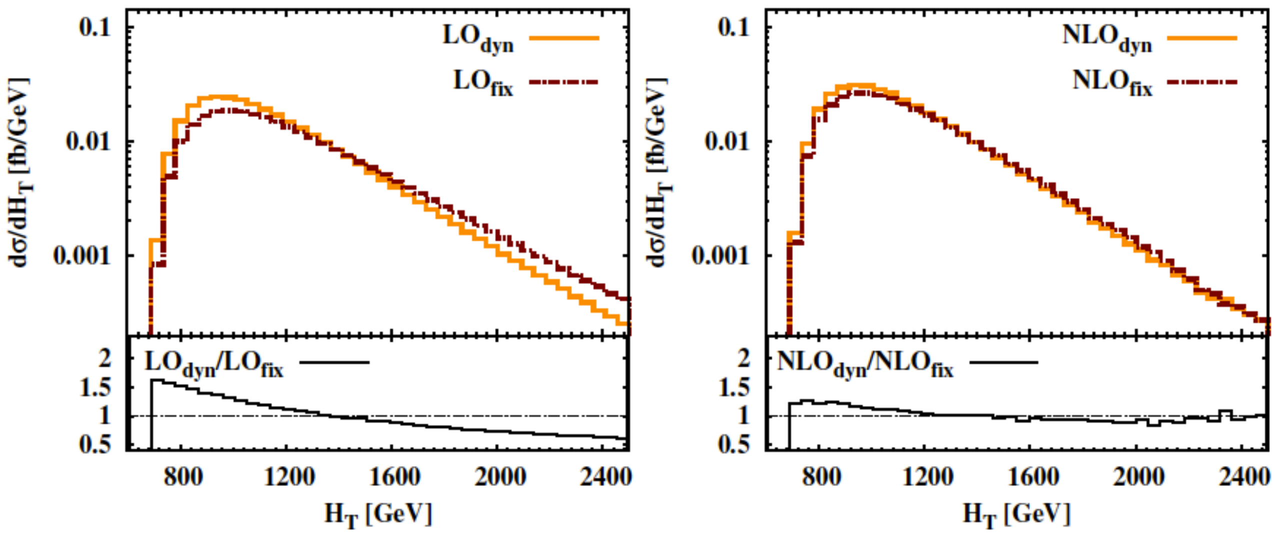
$\mu = H_T/4$



- Results for the integrated cross sections have only slightly changed
- Constant(-ish) differential K-factors for the distributions
- Moderate and positive corrections of the order or **20%** over the whole range
- NLO error bands fit within LO error bands

HELAC-NLO: Bevilacqua, Worek '12

Differential Distributions

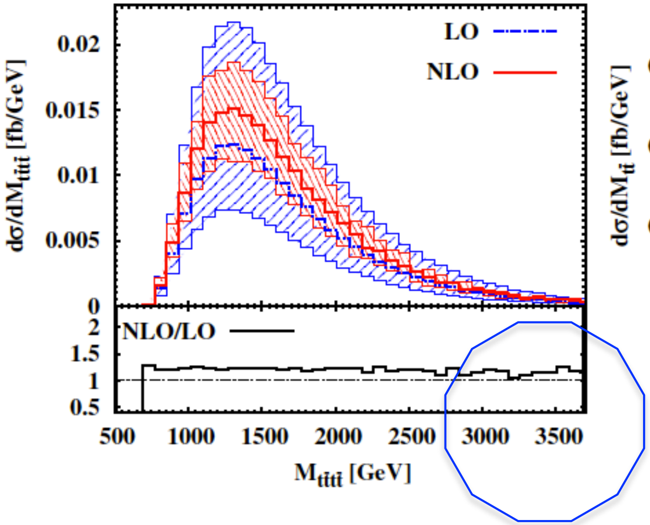


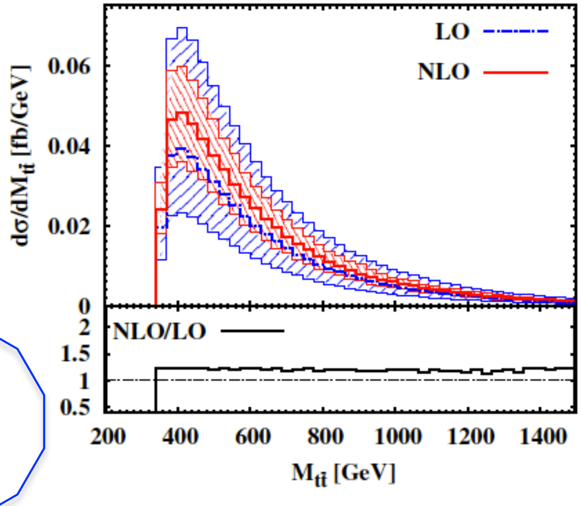
- Improvement obtained with a dynamic scale at NLO is moderate
- The change in the shape of LO distributions is rather strong

The fixed order approximation is meaningful, when the improved scale choice affects NLO cross sections to a much lower extent than the LO ones

HELAC-NLO: Bevilacqua, Worek '12

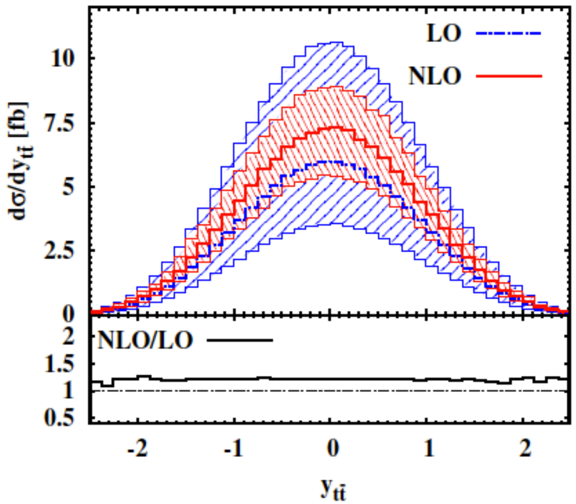
Differential Distributions

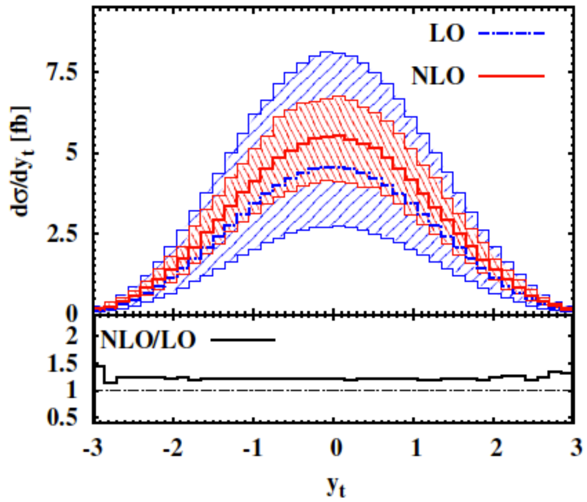




$\mu = H_T/4$

- ❑ Invariant mass of the tttt
- ❑ Invariant mass of the tt pair
- ❑ Rapidity of the tt pair
- ❑ Rapidity of top quark





- ❑ Differential K-factors are constant within the whole range

HELAC-NLO: Bevilacqua, Worek '12

Fixed Scale Vs Dynamical

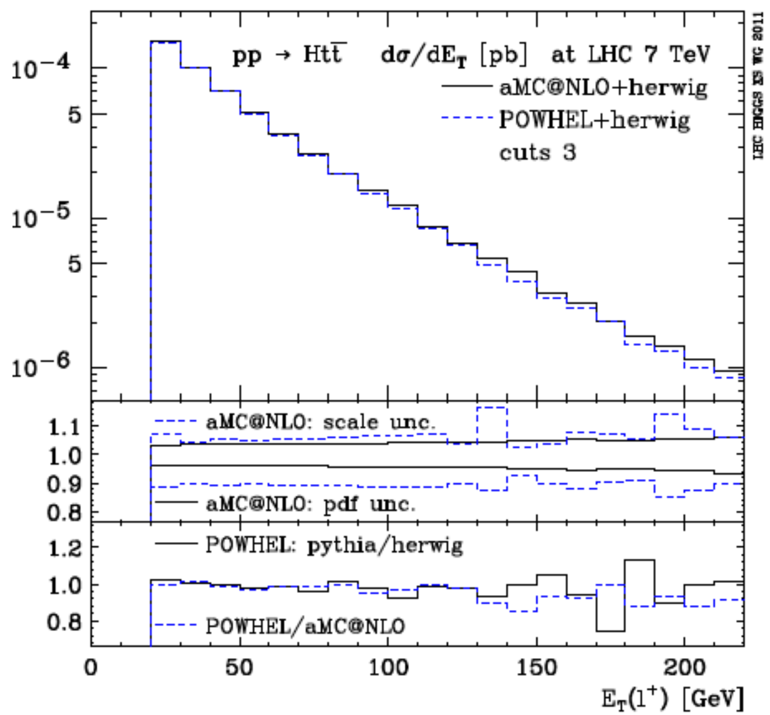
- Looking only at the total cross section both scale choices are in good shape
- Results agree well within the corresponding theoretical errors

- Differential cross sections show large distortions up to 80% for fixed scale
- Large negative corrections in the tails of several distributions
- Accurate description of the shapes of observables only via full NLO QCD

- Moderate, positive and almost constant corrections of the order of 20% for all the investigated observables for dynamical scale
- Efficiently accommodates for the multi-scale kinematics of the process
- Can be used in LO calculation together with some global K–factor
- Well approximate the full NLO QCD calculation
- Easily merged with parton shower programs to obtain realistic events

Top Anti-Top + V With PS

- Interface of NLO ttV (V=H, A, Z, W) calculations with parton-shower programs
- ttH/ttA @ LHC has been studied by aMC@NLO and POWHEL
- POWHEL = HELAC-NLO + POWHEG BOX
- aMC@NLO = MADLOOP + MC@NLO



LHC Higgs Cross Section Working Group:
S. Dittmaier, C. Mariotti, G. Passarino, R. Tanaka et al '12

- Other results:
  - ttH
  - ttZ
  - ttW

Garzelli, Kardos, Papadopoulos, Trocsanyi '11 '12

See poster by M. V. Garzelli:
"ttbar pair hadroproduction with a heavy boson at the NLO QCD + Parton Shower"

Summary And Outlook

- New problem at the LHC → multiparticle final states
- Hard emission is less suppressed at LHC energies
- Better understanding of the high-energy tails of distributions is needed
- Dynamic scales that depend on the event structure should be used

- Remarkable development in NLO calculations driven by the LHC needs
- 2 → 4(5) processes currently scrutinized @ NLO

- 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

- NNLO calculation for top anti-top pair @ TeVatron is now available

Bärnreuther, Czakon, Mitov '12