Next-to-Leading Order tt + Jets Physics with HELAC-NLO

Malgorzata Worek

Bergische Universität Wuppertal

TOP 2010 - 3rd International Workshop on Top Quark Physics, May 31 - June 4, Bruges, Belgium

Outline

- General Motivation for next-to-leading order calculations
- Why do we need **pp → ttH → ttbb, pp → ttbb** & **pp → ttjj** @ NLO ?
- **HELAC-NLO** framework in a nutshell
- Results for integrated and differential cross sections
- Summary & Outlook

HELAC-NLO Group:

G. Bevilacqua, INP Demokritos Athens, Greece
M. Czakon, RWTH Aachen, Germany
M.V. Garzelli, Granada University, Spain
A. van Hameren, INP Krakow, Poland
I. Malamos, Nijmegen University, Netherlands
C. G. Papadopoulos, INP Demokritos Athens, Greece
R. Pittau, Granada University, Spain
M. Worek, Wuppertal University, Germany

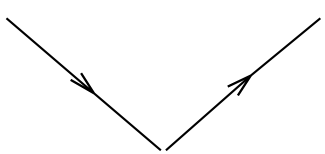
Contributors:

A. Kanaki
A. Cafarella
P. Draggiotis, Valencia University, Spain
G. Ossola, NY City College of Technology, USA

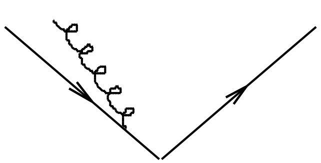
General Motivation for NLO

- Stabilizing the scale in the QCD input parameteres → the strong coupling constant and PDFs
- Normalization and shape of distributions first known at NLO
- Many scale processes: **V+ jets, VV + jets, ttH, tt + jets, n-jets ...**
- Sometimes dynamical scales seem to work better for some observables
- How to know that the scale is chosen properly ?
- Improved description of jets

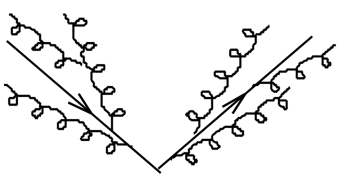
1 Jet 2 Jet



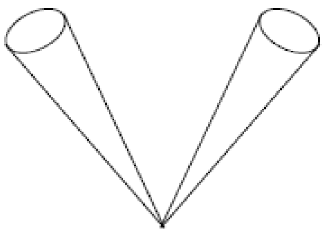
LO



NLO



Parton Shower



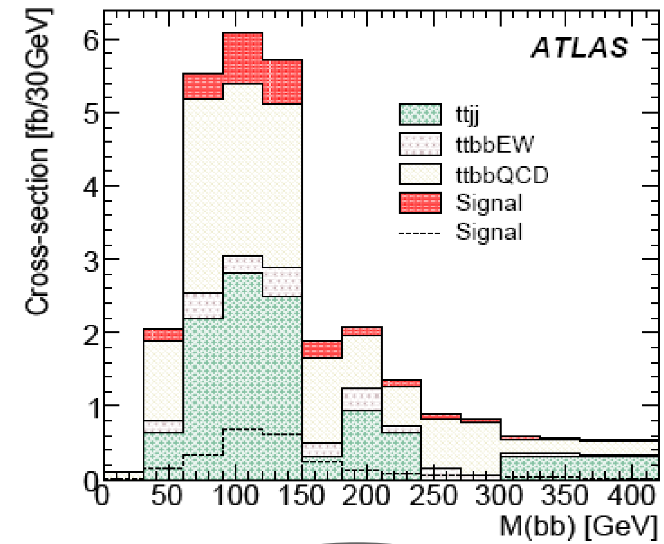
$pp \rightarrow ttH \rightarrow ttbb$

- **ttH:** potential discovery channel in low mass range where Higgs boson decay into **bb** pair

  $m_H \leq 135$ GeV

- Unique access to top & bottom Yukawa coupling
- Large QCD backgrounds: **ttjj & ttbb**
- **<u>Problem 1</u>** **combinatorial background of b-jets:** bb pair can be chosen incorectly, lack of distinctive kinematic feature of Higgs decay jets
- **<u>Problem 2</u>** **b-tagging efficiency:** two b-jets for Higgs candidate can arise from mistagged QCD light jets
- **<u>Goal:</u>** Backgrounds need to be very well controlled

ATLAS TDR, CERN-OPEN-2008-020

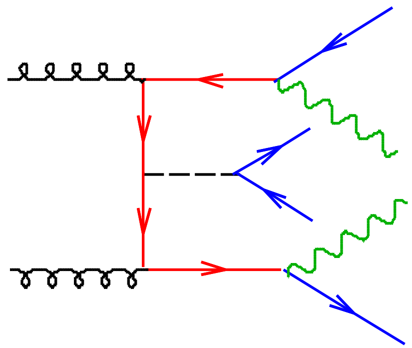


S/B ~ 1/9

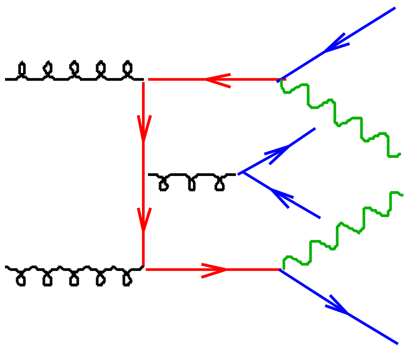
Summary table	Significance loose/tight	Luminosity
ATLAS (Lepton+jets)	2.2	30 fb^{-1}
CMS (Lepton+jets)	2.5/1.9	60 fb^{-1}
CMS(Combined)	3.9/3.3	60 fb^{-1}

G. Aad, J. Steggemann, ATLAS & CMS @ TOP 2008

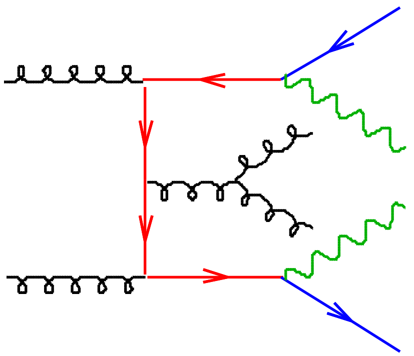
Example of Feynman Diagrams



Signal process **pp** → **ttH** → **ttbb**



Irreducible background process **pp** → **ttbb**



Reducible background process **pp** → **ttjj**

Theoretical Motivation

- NLO corrections to 2 → 4 is current technical frontier
- Complexity of calculations triggered creation of prioritized wishlist
- **ttbb** & **ttjj** productions range among the most wanted candidates

- NLO QCD corrections to **ttH** — *W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira, P.M. Zerwas '01; L. Reina, S. Dawson '01, S. Dawson, L.H. Orr, L. Reina, D. Wackeroth '03*
- NLO QCD corrections to **ttH → ttbb** — *G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek '10 (Les Houches 2009)*
- NLO QCD corrections to **ttbb** — *A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini '08, '09, '10; G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M.Worek '09*
- NLO QCD corrections to **ttjj** — *G. Bevilacqua, M. Czakon, C.G. Papadopoulos, M.Worek '10*

Goal: Demonstrate the power of **HELAC-NLO** system in realistic computation with 6 external legs and massive partons

Structure of NLO Calculations

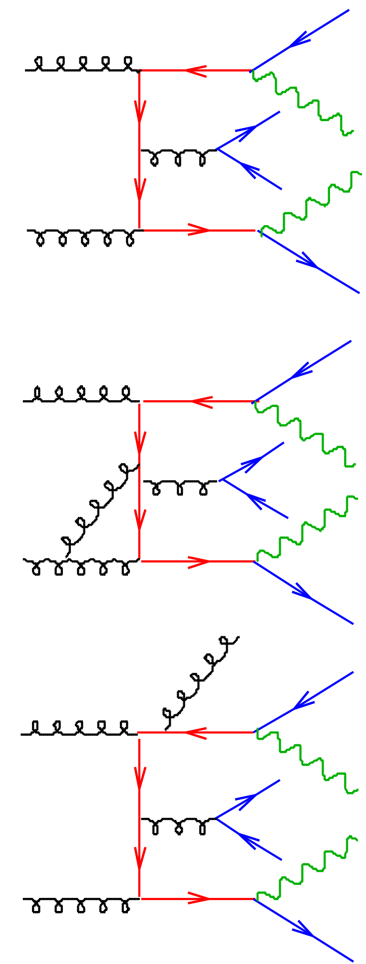
- **Subtraction method for NLO calculation**

S. Catani, M.H. Seymour '97
S. Catani, S. Dittmaier, M.H. Seymour, Z. Trocsanyi '02
M. Czakon, C. G. Papadopoulos, M. Worek '09

- Taken separately integrals are IR divergent → Only sum is finite
- Need to get individual contribution finite to perform MC integration

$$d\hat{\sigma}^{NLO} = \int_n d\hat{\sigma}^{LO} + \int_{n+1} d\sigma^{real} - \int_{n+1} d\sigma^{A} + \int_n d\sigma^{virt.} + \int_{n+1} d\sigma^{A} \Rightarrow$$

$$\int_{n+1} [d\sigma^{real} - d\sigma^{D}] + \int_n [d\sigma^{virt.} + d\sigma^{I} + d\sigma^{KP}]$$



- Local counter term added → proper approximation of $d\sigma^{real}$
- Process independent method, dipole functions, I and KP operators universal !

Our strategy in a few words:

- make it fully numeric
- make it fully automatic
- all summation via Monte Carlo

HELAC-NLO In A Nutshell

HELAC-PHEGAS

A. Kanaki, C. G. Papadopoulos '00
C. G. Papadopoulos '01
A. Cafarella, C. G. Papadopoulos, M. Worek '07

→ Event generator for all parton level processes at LO
→ http://helac-phegas.web.cern.ch/helac-phegas/

HELAC-1LOOP

A. van Hameren, C. G. Papadopoulos, R. Pittau '09

→ Evaluation of virtual one-loop amplitudes, based on **HELAC**

CUTTOOLS

G. Ossola, C. G. Papadopoulos, R. Pittau '07, '08
P. Draggiotis, M. V. Garzelli, C. G. Papadopoulos, R. Pittau '09

→ Reduction of tensor integrals and determination of coefficients via OPP reduction method
→ http://www.ugr.es/~pittau/CutTools

ONELOOP

→ Evaluation of scalar integrals (all divergent and finite scalar integrals are included)
→ http://annapurna.ifj.edu.pl/~hameren/

HELAC-DIPOLES

M. Czakon, C. G. Papadopoulos, M. Worek '09

→ Catani-Seymour dipole subtraction for massless and massive cases
→ Phase space integration of subtracted real radiation and integrated dipoles (**I** & **KP** operators)
→ Arbitrary polarizations & phase space restriction on dipoles contribution
→ http://helac-phegas.web.cern.ch/helac-phegas/

Virtual Timings

process	full color sum [s]	color sampling [s] (100 event average)
$gg \to t\bar{t}H^* \to t\bar{t}b\bar{b}$	0.77	0.20
$gg \to t\bar{t}b\bar{b}$	8.25	0.82
$gg \to t\bar{t}gg$	122.5	5.79

- Lahey Fortran Compiler on 3 GHz Intel Xeon
- Maybe a factor of 2 due to compiler and option (??)
- Random helicity everywhere !

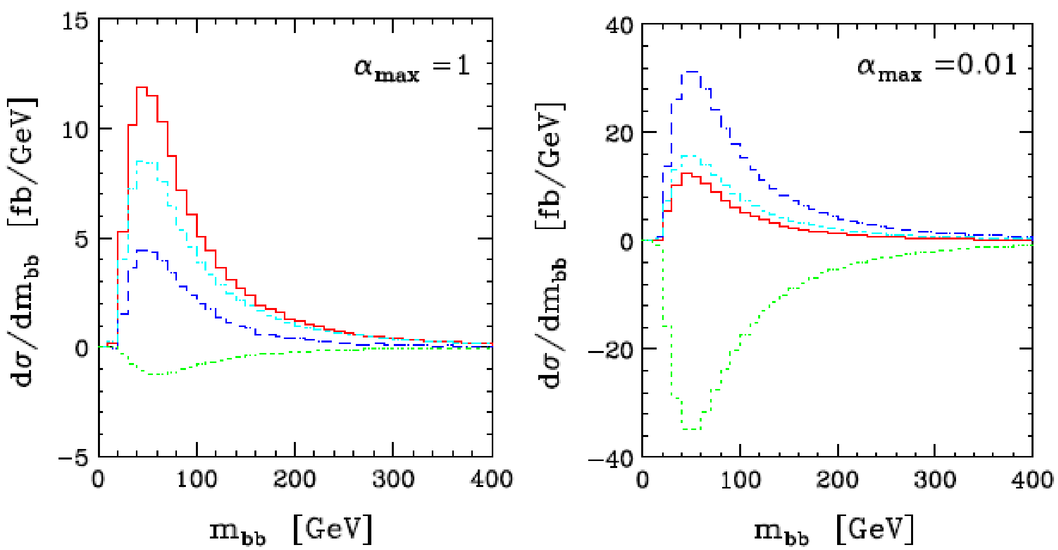
Real Emission Timings

PROCESS	REAL EMISSION + DIPOLES [msec]	REAL EMISSION [msec]	NR OF DIPOLES
$gg \to ggg$	3.8	1.0	27
$gg \to gggg$	8.5	2.6	56
$gg \to ggggg$	300	42	100
$u\bar{d} \to W^+ gggg$	9.3	2.4	56
$gg \to t\bar{t}b\bar{b}g$	12	2.9	55

- Timings obtained on Core 2 Duo 2.53 GHz machine with Intel Fortran
- All dipoles included ($\alpha_{max} = 1$)
- Random helicity everywhere !

Real Emission for pp → ttbb

Different parts of real radiation contribution with different choices of α_{max}



Subtracted real emission

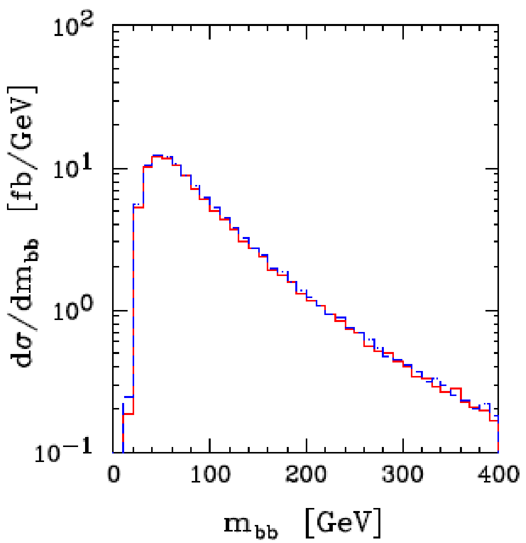
K + P operators

I operators

Full result

Internal check:

Cutoff independence !!



Phase space restriction on the dipoles phase space $\alpha_{max} \in (0,1]$

- Less dipole subtraction terms per event
- Increased numerical stability by decreasing size of dipole phase space
- Reduced missed binning problem
- Large cancellations between real radiation and integrated dipoles

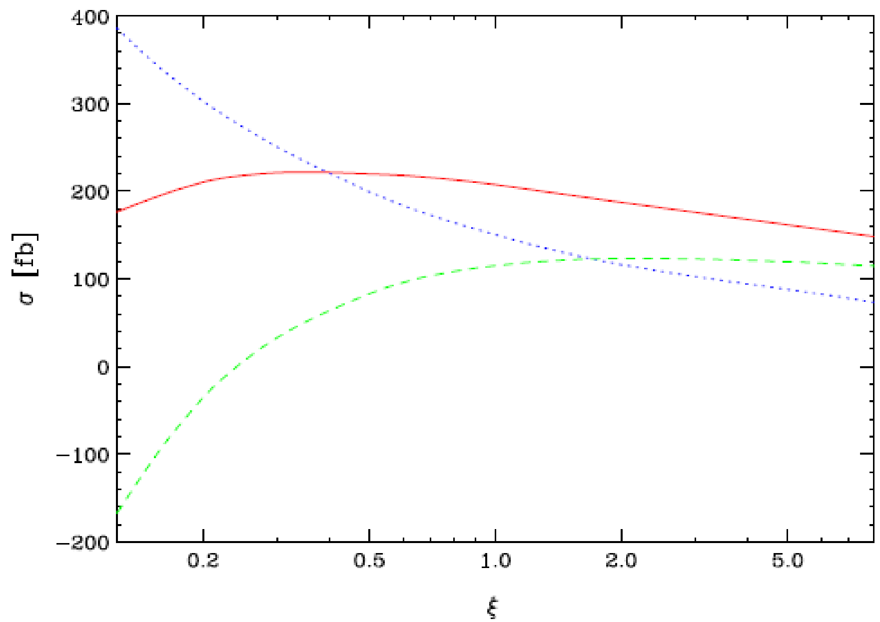
G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09

$pp \to ttH \to ttbb$ @ LHC

$\sqrt{s} = 14$ TeV
$p_T(j) > 20$ GeV
$|y(j)| < 2.5$
$\Delta R(j,j) > 0.8$
$\mu_R = \mu_F = m_{top} + m_H/2$
$m_H = 130$ GeV
CTEQ6L1, CTEQ6M
k_T algorithm R= 0.8

pp → ttH → ttbb @ LHC

Scale Dependence and Integrated Cross Sections



$$\sigma^{\mathrm{S}}_{\mathrm{LO}} = (150.375 \pm 0.077)\ \mathrm{fb}$$

$$\sigma^{\mathrm{S}}_{\mathrm{NLO}} = (207.268 \pm 0.150)\ \mathrm{fb}$$

$$\sigma^{\mathrm{S}}_{\mathrm{NLO-veto}} = (114.880 \pm 0.152)\ \mathrm{fb}$$

Scale dependence reduced:
33% at **LO** → **10%** at **NLO**
28% at **NLO with jet Veto** of 50 GeV

K factor of **K = 1.38** **(K = 0.76)**
NLO QCD Corrections **38%** **(-24%)**

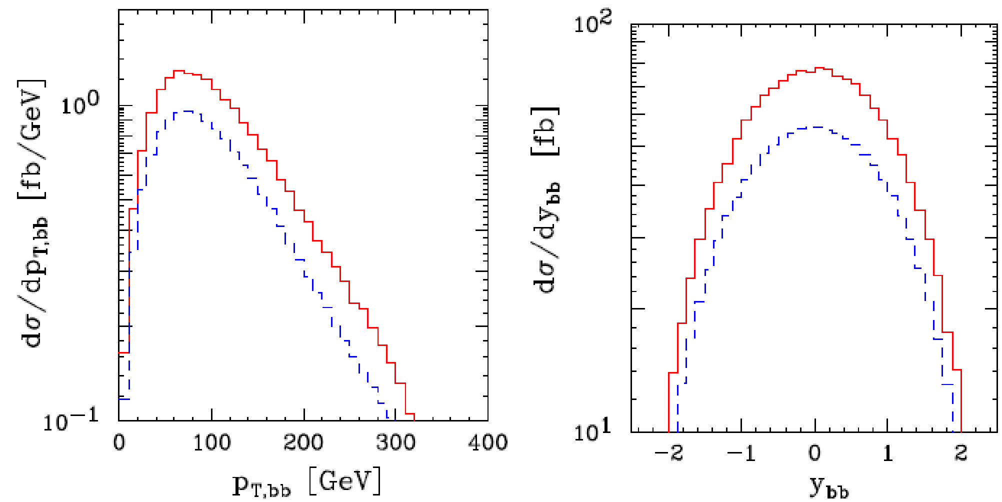
G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek '10 (Les Houches 2009)

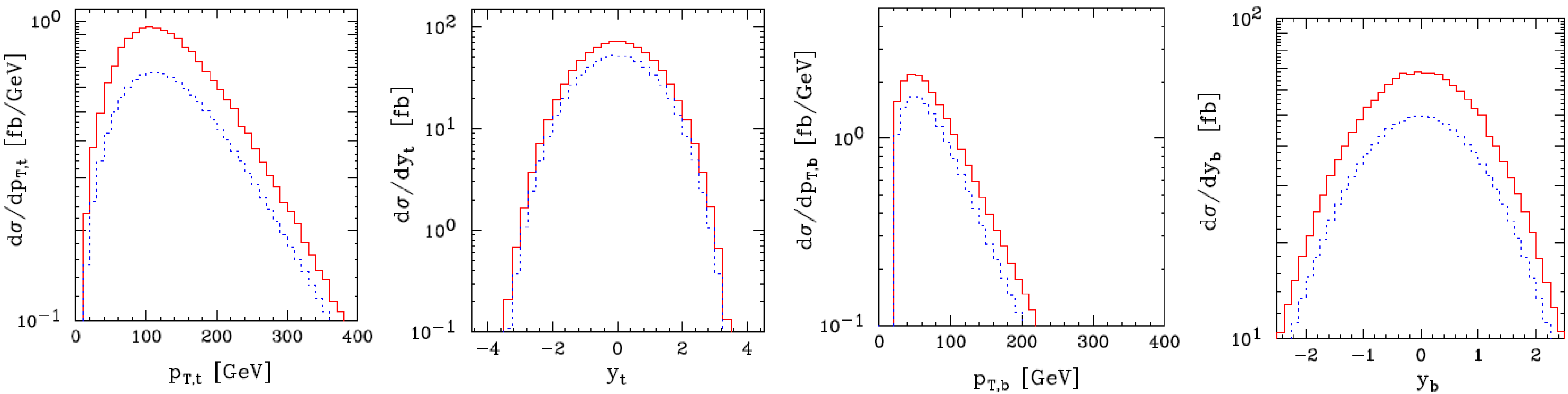
pp → ttH → ttbb @ LHC

LO & **NLO**

- **bb pair kinematics**
  → Transverse momentum
  → Rapidity distribution

- **single b & top kinematics**
  → Transverse momentum
  → Rapidity distribution





G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek '10 (Les Houches 2009)

$pp \to t\bar{t}b\bar{b}$ @ LHC

$\sqrt{s}$ = 14 TeV
$p_T(j) > 20$ GeV
$|y(j)| < 2.5$
$\Delta R(j,j) > 0.8$
$\mu_R = \mu_F = m_{top}$
CTEQ6L1, CTEQ6M
k_T algorithm R = 0.8

$pp \rightarrow ttbb$ @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini '08, '09

Permille level agreement!

Process	$\sigma^{LO}_{[23,\,24]}$ [fb]	σ^{LO} [fb]	$\sigma^{NLO}_{[23,\,24]}$ [fb]	$\sigma^{NLO}_{\alpha_{max}=1}$ [fb]	$\sigma^{NLO}_{\alpha_{max}=0.01}$ [fb]
$q\bar{q} \rightarrow t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)	87.581(134)
$pp \rightarrow t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)	2636(3)

m_{top} = 172.6 GeV

$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
σ^{LO} [fb]	8885(36)	2526(10)	1489.2(0.9)	923.4(3.8)	388.8(1.4)
σ^{NLO} [fb]	4213(65)	3498(11)	2636(3)	1933.0(3.8)	1044.7(1.7)

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

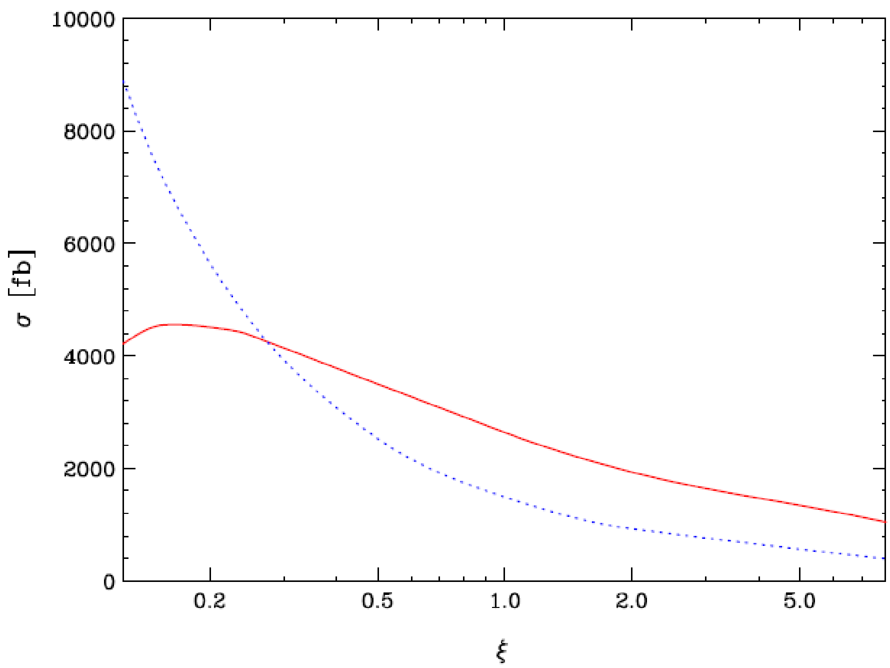
$$\sigma^{NLO}_{t\bar{t}b\bar{b}} = 2636 \begin{array}{l} +862\ (33\%) \\ -703\ (27\%) \end{array} \text{ fb}$$

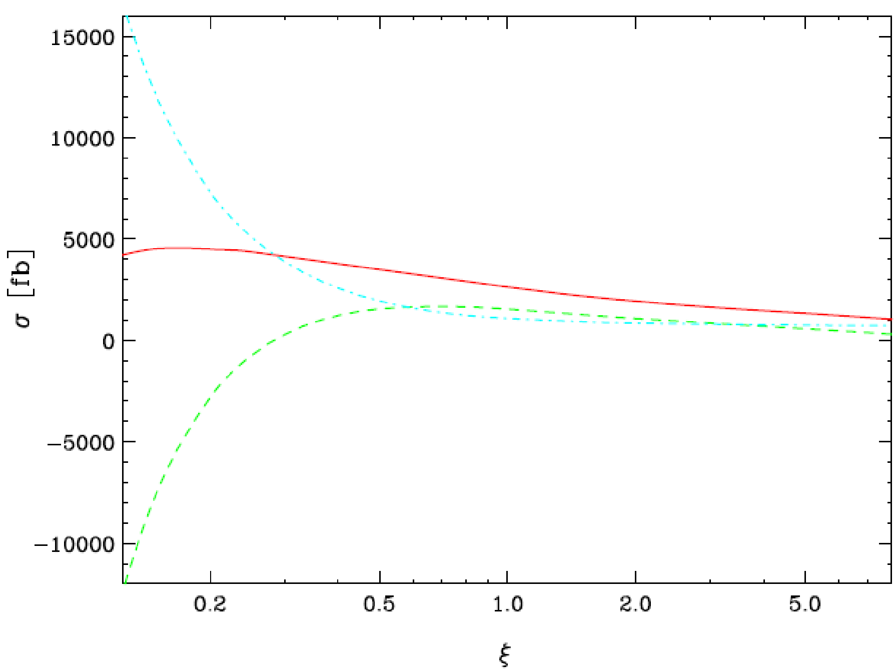
Scale dependence reduced:
70% at **LO** → **33%** at **NLO**

K factor of **K = 1.77**
for quarks only **K = 1.03**
With jet veto of 50 GeV **K = 1.20**

pp → ttbb @ LHC

Scale Dependence



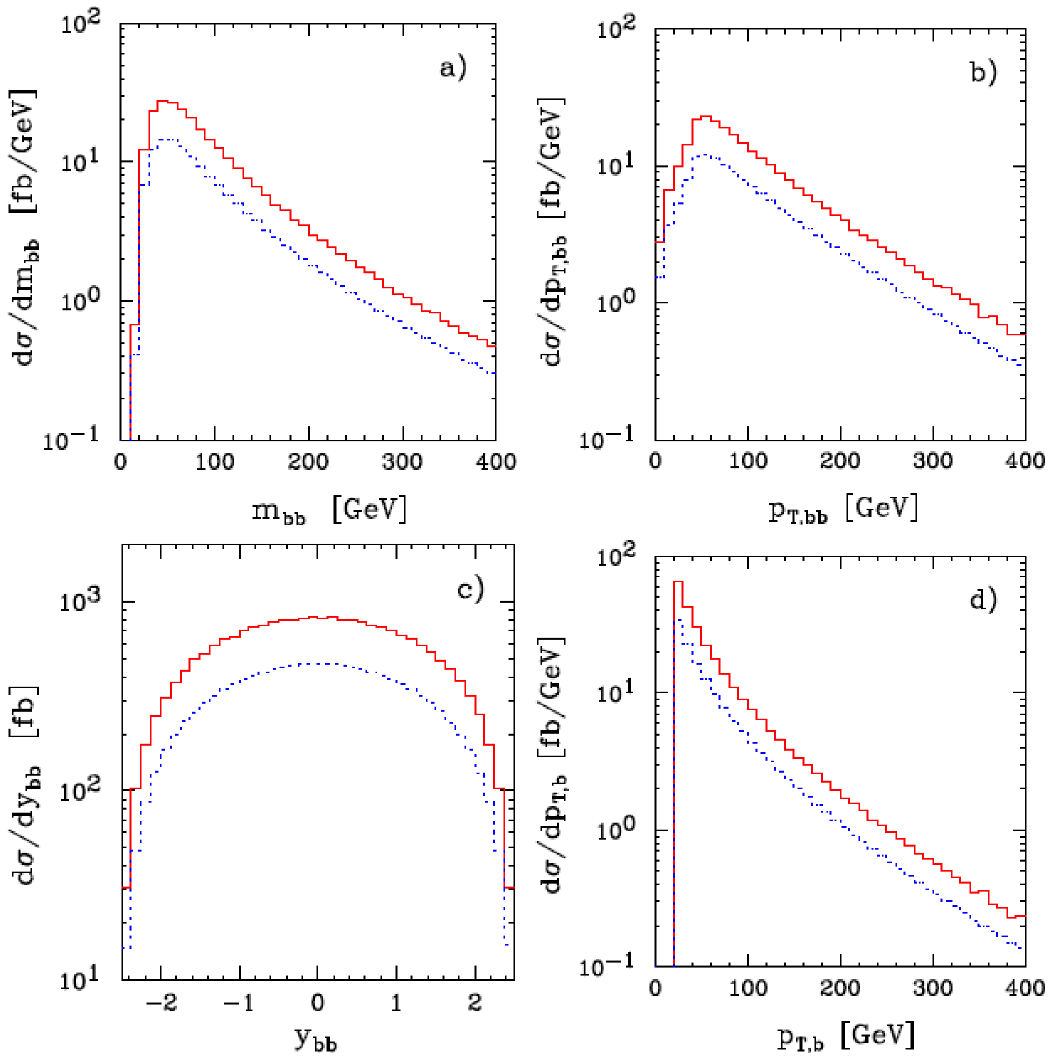


- Varying scale up or down by a factor 2 changes cross section by **70%** at **LO** and by **33%** at **NLO**
- Scale dependence at **NLO** decomposed into contribution of **Virtual Corrections** & **Real Radiation**

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09

pp → ttbb @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek '09



- **b-jet pair kinematics**

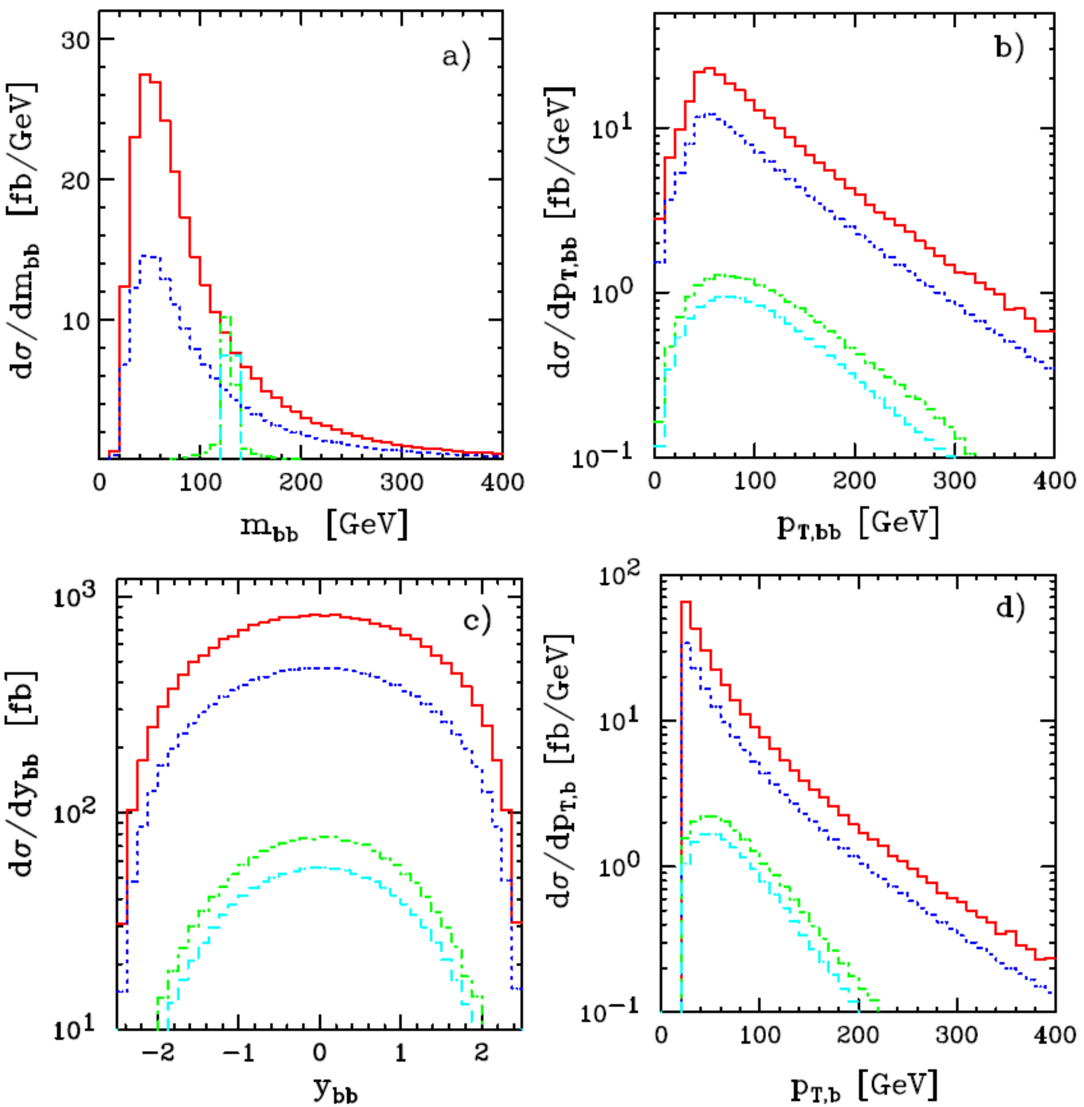
  → Invariant mass distribution
  → Transverse momentum
  → Rapidity distribution

- **single b-jet kinematics**

  → Transverse momentum

- **LO** & **NLO**
- Relatively small variation compared to the size but shape change important

Signal & Background pp → ttbb



Background pp → ttbb
LO & **NLO**

Signal pp → ttH → ttbb
LO & **NLO**

On-shell top !

b-jet pair kinematics

→ Invariant mass distribution
→ Transverse momentum
→ Rapidity distribution

single b-jet kinematics

→ Transverse momentum

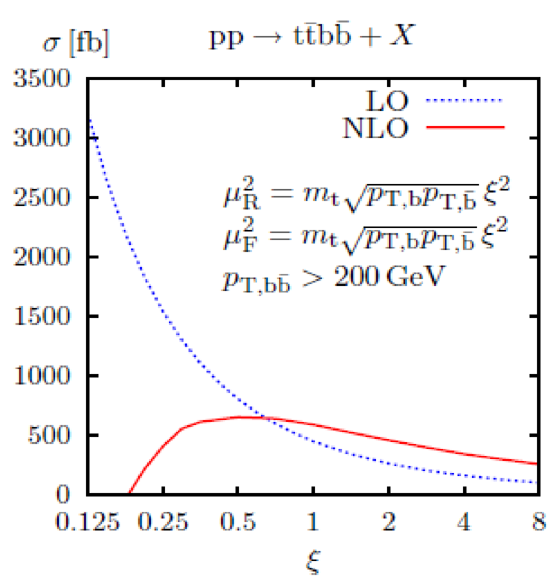
G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek '10 (Les Houches 2009)

pp → ttbb @ LHC

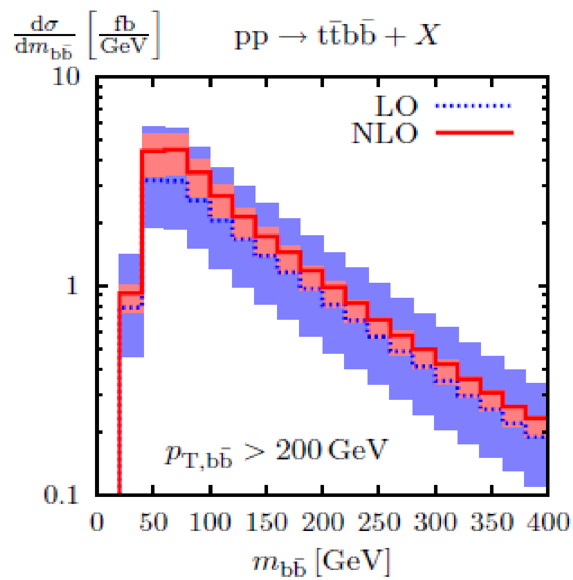
A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini '10

- LO & NLO integrated cross sections in fb
- Scale variations by factor 2
- K-factors

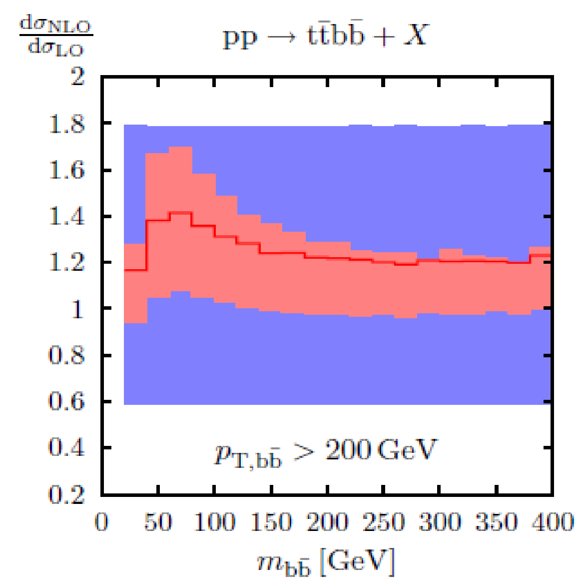
Setup	$m_{b\bar{b},\mathrm{cut}}$	$p_{\mathrm{T},b\bar{b},\mathrm{cut}}$	$p_{\mathrm{jet,veto}}$	$p_{\mathrm{T,b,cut}}$	$y_{\mathrm{b,cut}}$	σ_{LO}	σ_{NLO}	K
I	100	-	-	20	2.5	$786.3(2)^{+78\%}_{-41\%}$	$978(3)^{+13\%}_{-21\%}$	1.24
II	-	200	-	20	2.5	$451.8(2)^{+79\%}_{-41\%}$	$592(4)^{+13\%}_{-22\%}$	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



Scale dependence for dynamic scale



m_{bb} distribution



Dynamic K-factor

$pp \to t\bar{t}jj$ @ LHC

$\sqrt{s} = 14$ TeV
$p_T(j) > 50$ GeV
$|y(j)| < 4.5$
$\Delta R(j,j) > 1.0$
$\mu_R = \mu_F = m_{top}$
CTEQ6L1, CTEQ6M
k_T algorithm $R = 0.8$

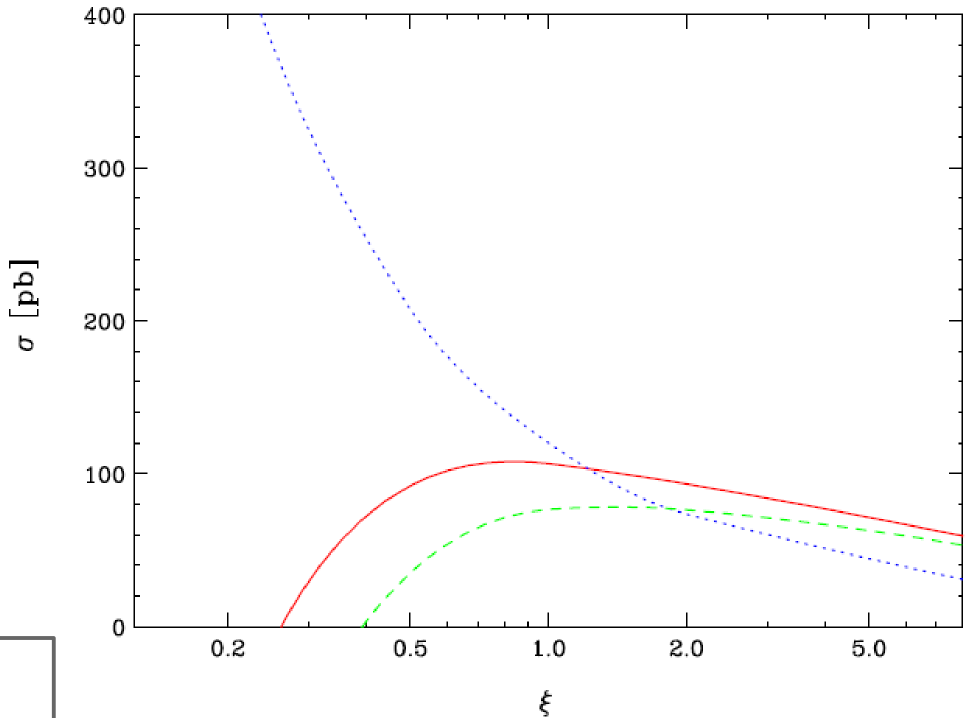
pp → ttjj @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek '10

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 %

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

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



Scale dependence reduced:

72% at **LO** → **13%** at **NLO**

54% at **NLO with jet Veto** of 50 GeV

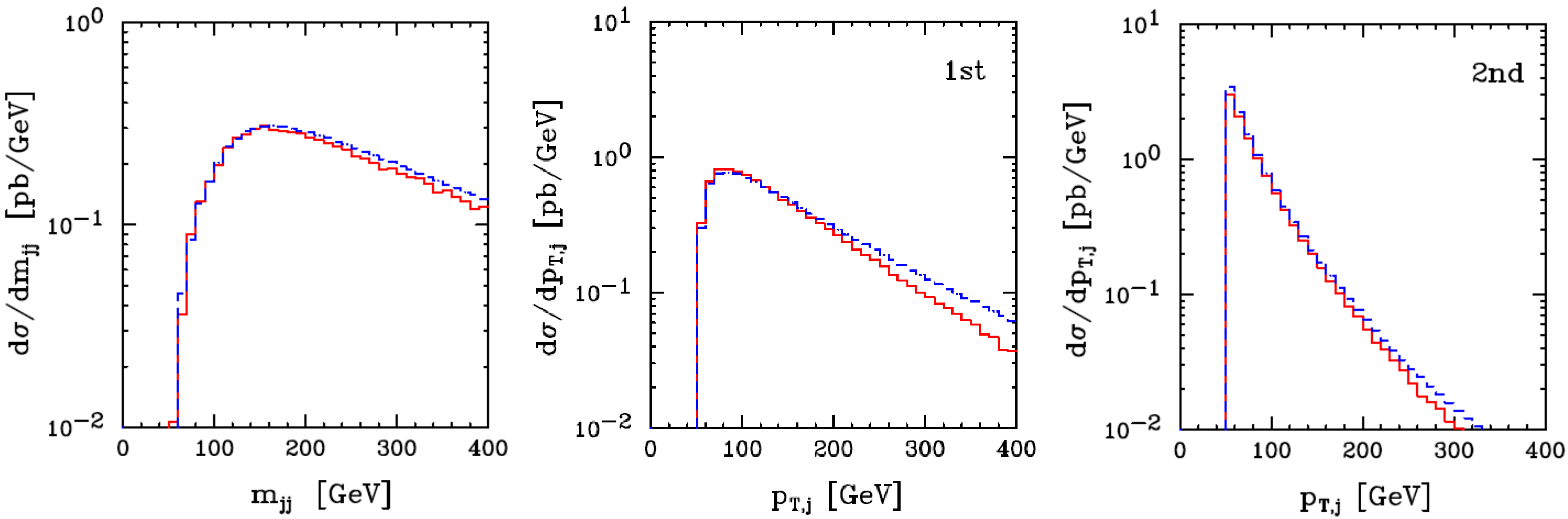
K factor of **K = 0.89** **(K = 0.64)**

→ Negative shift of **11%** **(36%)**

m_{top} = 172.6 GeV

pp → ttjj @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek '10



invariant mass of 2 jet system

→ size of the corrections transmitted to the distributions for low p_T

→ shapes change for hight p_T

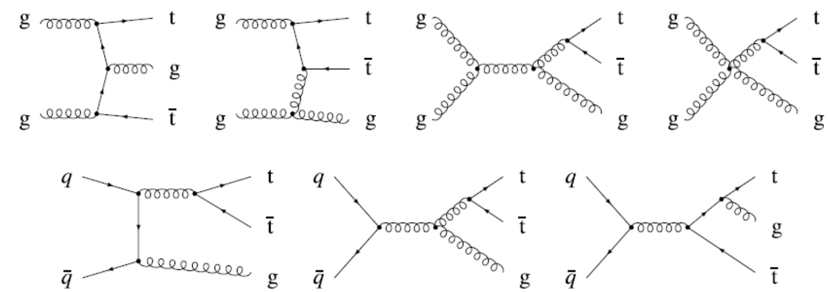
p_T of 1st hardest and 2nd hardest jet (ordered in p_T)

altered shapes up to **-39%, -28%** in tails

LO & **NLO**

pp → ttj @ LHC

- Results of previous study of **pp → ttj** have been reproduced for the first time !
- Cross section for different values of p_T jet cut
- Behavior of the corrections for different setups
- Argument that our conclusions for **pp → ttjj** will remain true for other input parameters



G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek '10

σ_{HELAC_NLO} = 376.6(6) pb

$p_{T,\mathrm{jet,cut}}$ [GeV]	$\sigma_{t\bar{t}\mathrm{jet}}$ [pb]	
	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	$46.67(6)^{+26}_{-15}$	$52.81(8)^{+0.8}_{-6.7}$

S. Dittmaier, P. Uwer, S. Weinzierl '07, '09

K_{20} = 0.97 (-3%)
K_{50} = 1.15 (15%)
K_{100} = 1.19 (19%)
K_{200} = 1.13 (13%)

Summary & Outlook

- Automated approach **HELAC-NLO**
- First results have already been presented:
  - ♣ **pp → ttj** (3 independent groups)
  - ♣ **pp → ttbb** (2 independent groups)
  - ♣ **pp → ttH → ttbb**
  - ♣ **pp → ttjj**
- Results of previous study of **pp → ttj** have been reproduced for the first time
- Phenomenological study for pp → ttH → ttbb, pp → ttbb, pp → ttjj
- Much wider study for pp → ttjj: variation of the center of mass energy, cone size in jet algorithm, transverse momentum cuts, jet vetoes, ...
- Other general & automatic systems: **BLACKHAT/SHERPA, ROCKET/MCFM, GOLEM, ...**

Outlook

More 2 $\rightarrow$ 4 processes in preparation

Single boson	Diboson	Triboson	Heavy flavor
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		$b\bar{b}\,t\bar{t}$
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		