

A nighttime photograph of a historic Italian town, likely Florence, featuring a stone bridge over a river. The buildings are illuminated with warm lights, and the bridge's arches and lights are reflected in the water. The sky is dark with some clouds.

Next-to-Leading Order $t\bar{t}$ + Jets Physics with HELAC-NLO

Malgorzata Worek
Wuppertal University

Outline

- General Motivation for next-to-leading order calculations
- Why do we need $pp \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$, $pp \rightarrow t\bar{t}b\bar{b}$ & $pp \rightarrow t\bar{t}j\bar{j}$ @ NLO ?
- **HELAC-NLO** framework in a nutshell
- Results for integrated and differential cross sections
- Summary & Outlook

HELAC-NLO Group:

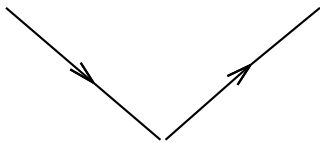
G. Bevilacqua, INP Demokritos Athens, Greece
M. Czakon, RWTH Aachen, Germany
M.V. Garzelli, Granada University, Spain
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Contributors:

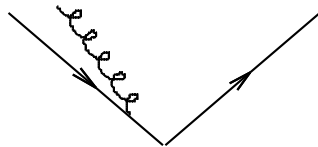
A. Kanaki
A. Cafarella
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General Motivation for NLO

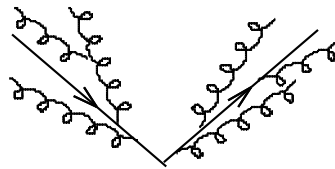
- Stabilizing the scale in the QCD input parameters \rightarrow the strong coupling constant and PDFs
- Normalization and shape of distributions first known at NLO
- Many scale processes: **V + jets, VV + jets, ttH, tt + jets, n-jets ...**
- Sometimes dynamical scales seem to work better for some observables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



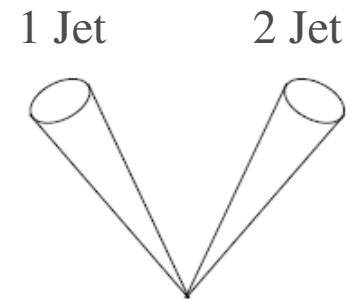
LO



NLO



Parton Shower



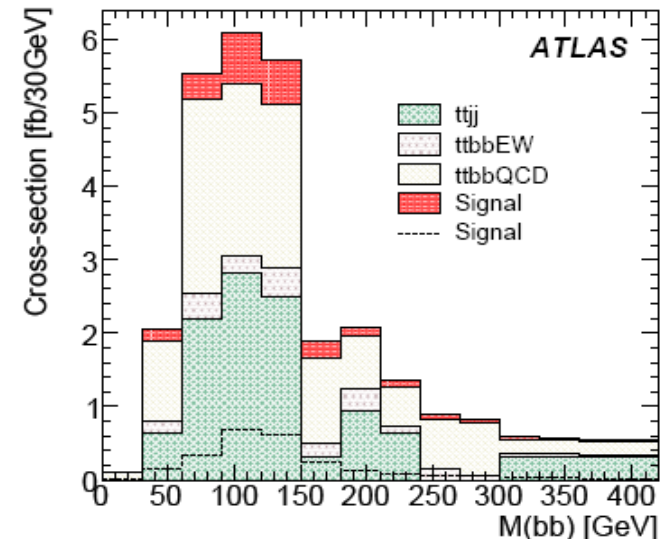
pp \rightarrow ttH \rightarrow ttbb

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

$$m_H \leq 135 \text{ GeV}$$

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

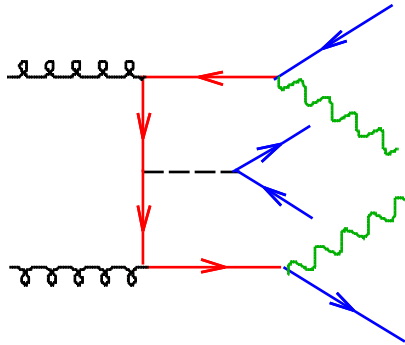
ATLAS TDR, CERN-OPEN-2008-020



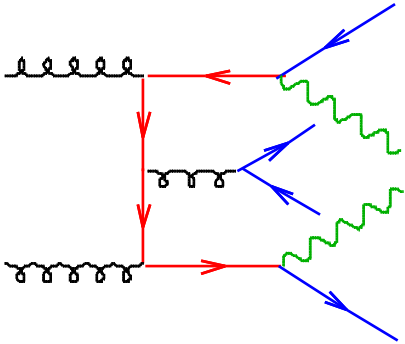
$S/B \sim 1/9$

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

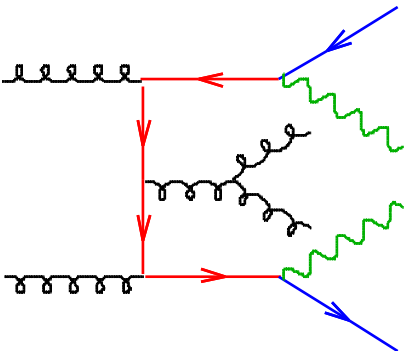
Example of Feynman Diagrams



Signal process $pp \rightarrow ttH \rightarrow ttbb$



Irreducible background process $pp \rightarrow ttbb$

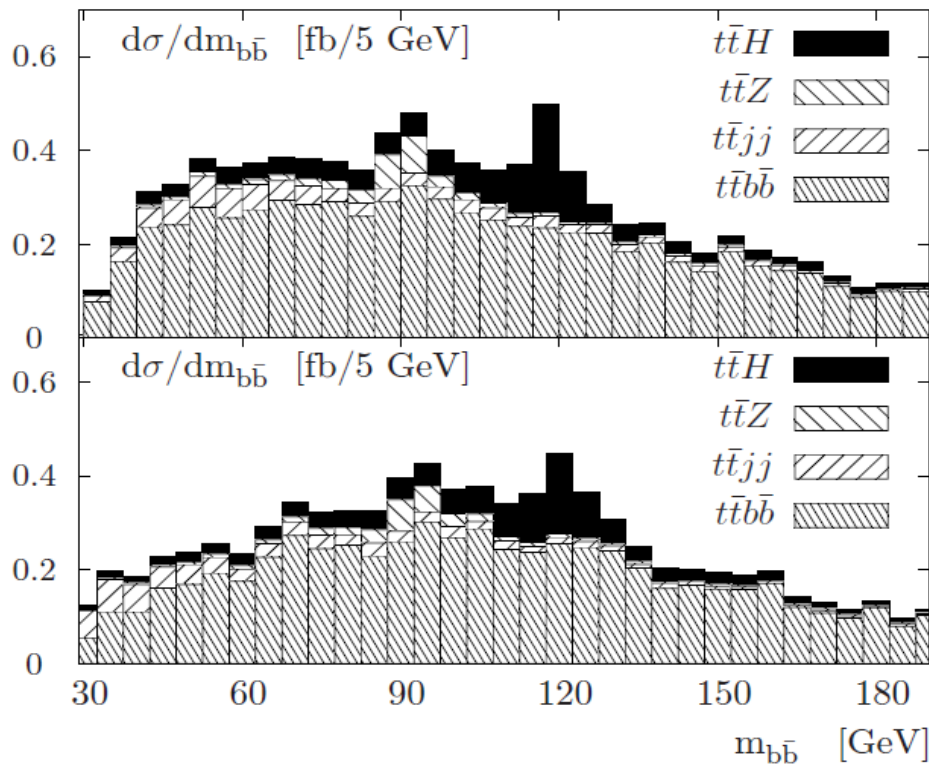


Reducible background process $pp \rightarrow ttjj$

Fat Jets in $pp \rightarrow ttH \rightarrow ttbb$

- ttH search with boosted heavy states with $p_T(j) > 200$ GeV \rightarrow no combinatorial background !

T. Plehn, G. P. Salam, M. Spannowsky '10



Double b tag

$\mathcal{L} = 100 \text{ fb}^{-1}$	S	B	S/B	S/\sqrt{B}
$m_H = 115 \text{ GeV}$	120	380	1/3.2	6.2
120 GeV	100	380	1/3.8	5.1
130 GeV	51	330	1/6.5	2.8

Triple b tag

$\mathcal{L} = 100 \text{ fb}^{-1}$	S	B	S/B	S/\sqrt{B}
$m_H = 115 \text{ GeV}$	57	118	1/2.1	5.2 (5.7)
120 GeV	48	115	1/2.4	4.5 (5.1)
130 GeV	29	103	1/3.6	2.9 (3.0)

- **Goal:** Determine whether NLO QCD corrections affect strongly $ttbb$ & $ttjj$ channels

Theoretical Motivation

- NLO corrections to $2 \rightarrow 4$ 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. Wackerath '03*

- NLO QCD corrections to **ttH** \rightarrow **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

NLO In A Nutshell

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

Subtraction method for NLO calculation

$$d\sigma_{pp}^{NLO} = \sum_{ij} \int dx_1 dx_2 f_i^p(x_1, \mu) f_j^p(x_2, \mu) d\hat{\sigma}_{ij}^{NLO}(x_1, x_2, \mu)$$

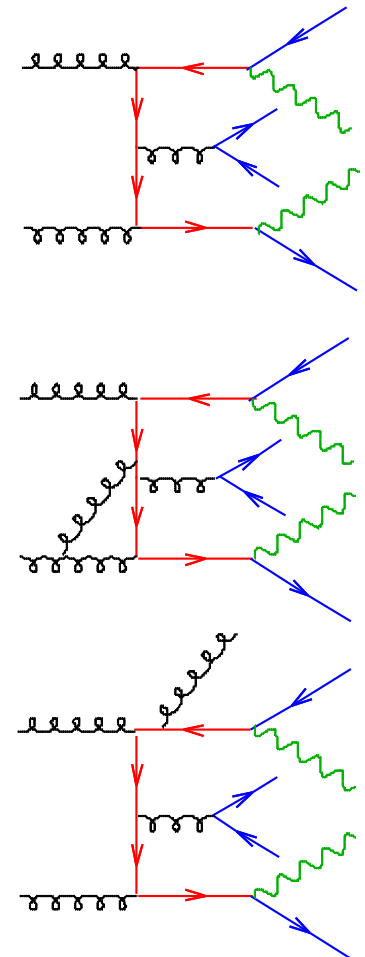
$$d\hat{\sigma}^{NLO} = \int_n d\hat{\sigma}^{LO} + \int_n d\sigma^{virt.} + \int_{n+1} d\sigma^{real}$$

- 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 $d\sigma^{real}$
- Same singular behaviour, integrated over unresolved 1-parton phase space
- Process independent method, dipole functions, I and KP operators universal !



HELAC-NLO In A Nutshell



HELAC-PHEGAS

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

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

HELAC-1LOOP

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

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

CUTTOOLS

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

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

ONELOOP

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

HELAC-DIPOLES

- 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/>

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

$pp \rightarrow ttH \rightarrow ttbb$ @ LHC



$$\sqrt{s} = 14 \text{ TeV}$$

$$p_T(j) > 20 \text{ GeV}$$

$$|y(j)| < 2.5$$

$$\Delta R(j,j) > 0.8$$

$$\mu_R = \mu_F = m_{\text{top}} + m_H/2$$

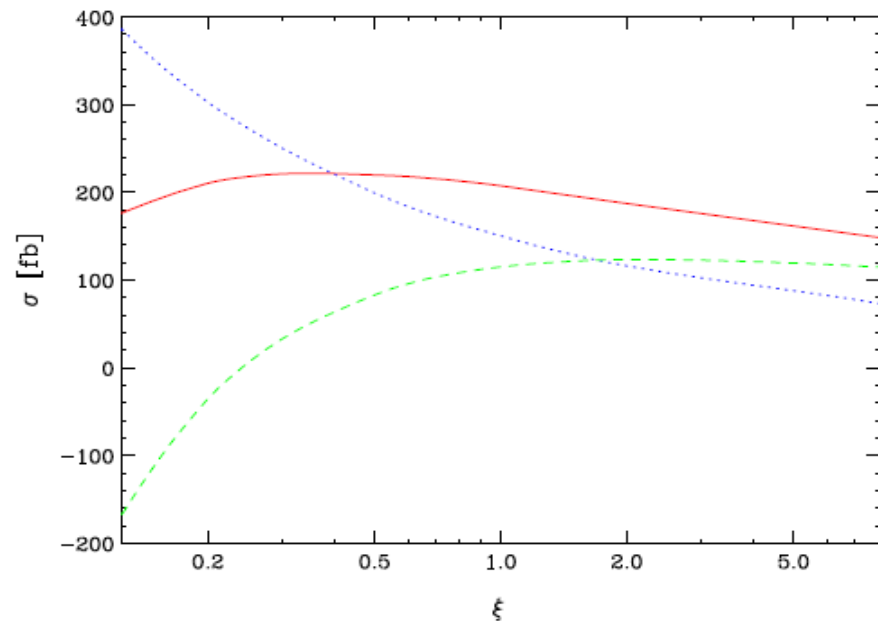
$$m_H = 130 \text{ GeV}$$

CTEQ6L1, CTEQ6M

k_T algorithm $R=0.8$

pp \rightarrow ttH \rightarrow ttbb @ LHC

Scale Dependence and Integrated Cross Sections



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

$$\begin{aligned}\sigma_{\text{LO}}^{\text{S}} &= (150.375 \pm 0.077) \text{ fb} \\ \sigma_{\text{NLO}}^{\text{S}} &= (207.268 \pm 0.150) \text{ fb} \\ \sigma_{\text{NLO-veto}}^{\text{S}} &= (114.880 \pm 0.152) \text{ fb}\end{aligned}$$

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

$pp \rightarrow ttH \rightarrow ttbb$ @ LHC

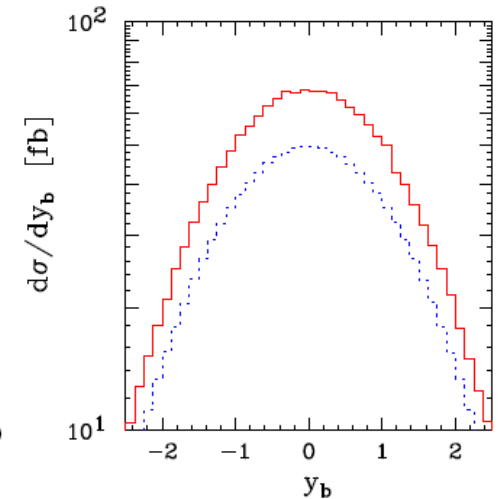
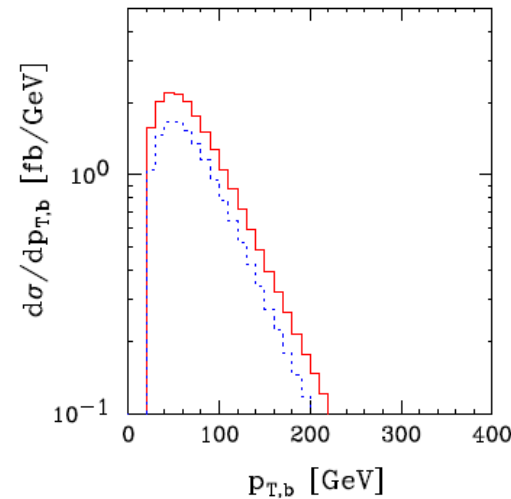
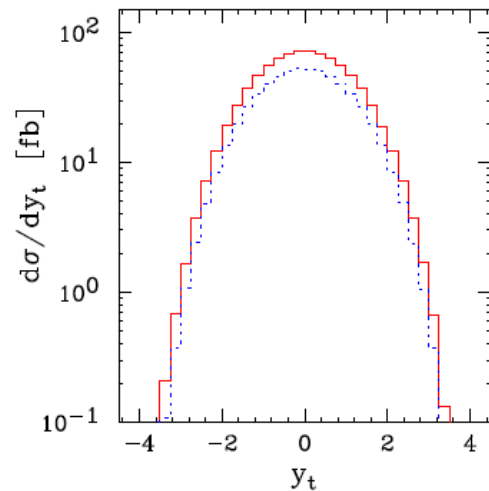
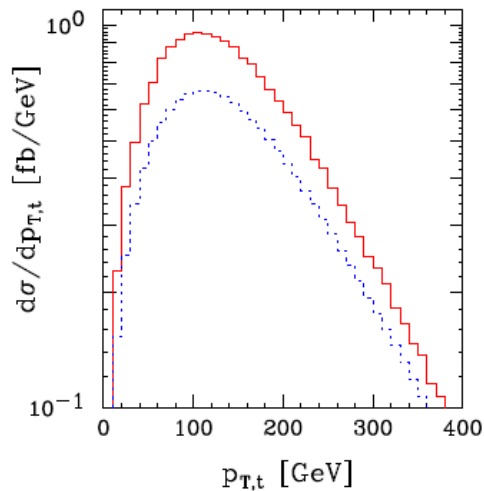
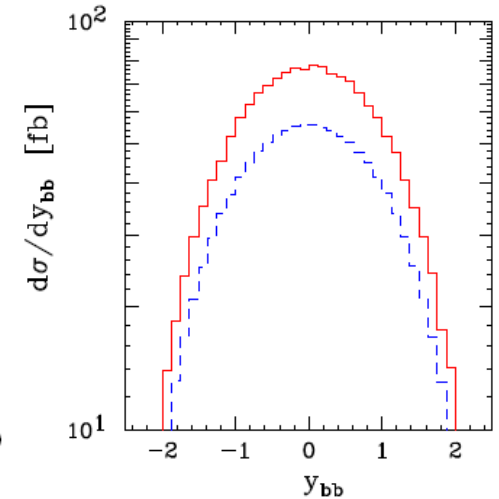
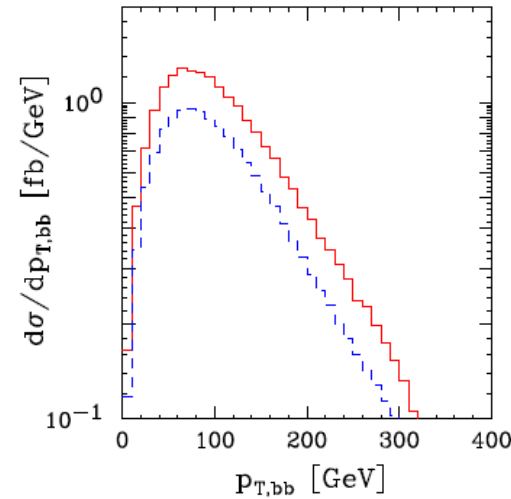
LO & NLO

● bb pair kinematics

- Transverse momentum
- Rapidity distribution

● single b & top kinematics

- Transverse momentum
- Rapidity distribution



pp \rightarrow ttbb @ LHC



$$\sqrt{s} = 14 \text{ TeV}$$

$$p_T(j) > 20 \text{ GeV}$$

$$|y(j)| < 2.5$$

$$\Delta R(j,j) > 0.8$$

$$\mu_R = \mu_F = m_{\text{top}}$$

CTEQ6L1, CTEQ6M

k_T algorithm $R = 0.8$

pp → ttbb @ LHC

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

Per mille level agreement!

Process	$\sigma_{[23, 24]}^{\text{LO}}$ [fb]	σ^{LO} [fb]	$\sigma_{[23, 24]}^{\text{NLO}}$ [fb]	$\sigma_{\alpha_{\text{max}}=1}^{\text{NLO}}$ [fb]	$\sigma_{\alpha_{\text{max}}=0.01}^{\text{NLO}}$ [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)

$m_{\text{top}} = 172.6 \text{ GeV}$

$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
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)

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

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

Scale dependence reduced:

70% at **LO** → **33%** at **NLO**

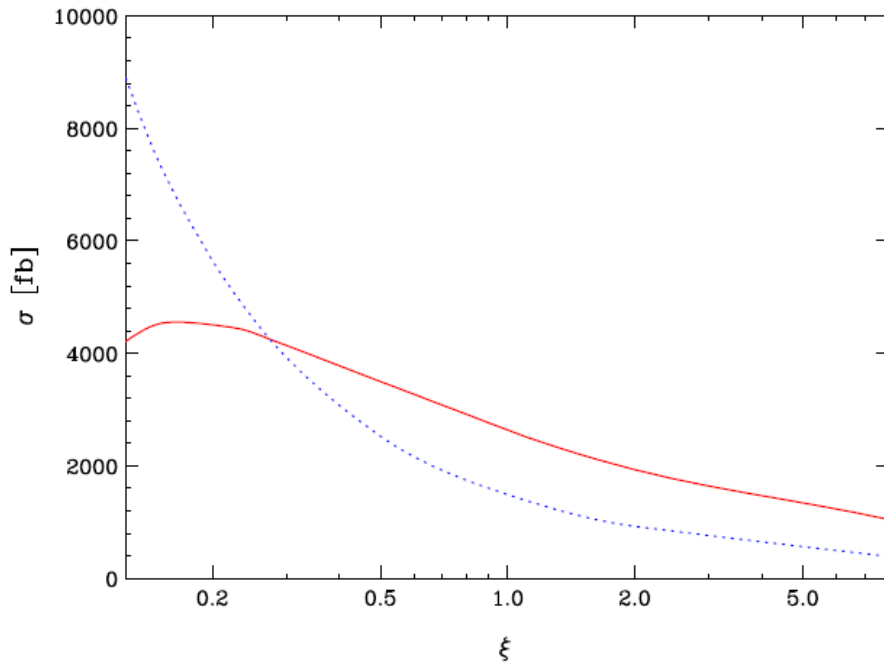
K factor of **K = 1.77**

for quarks only **K = 1.03**

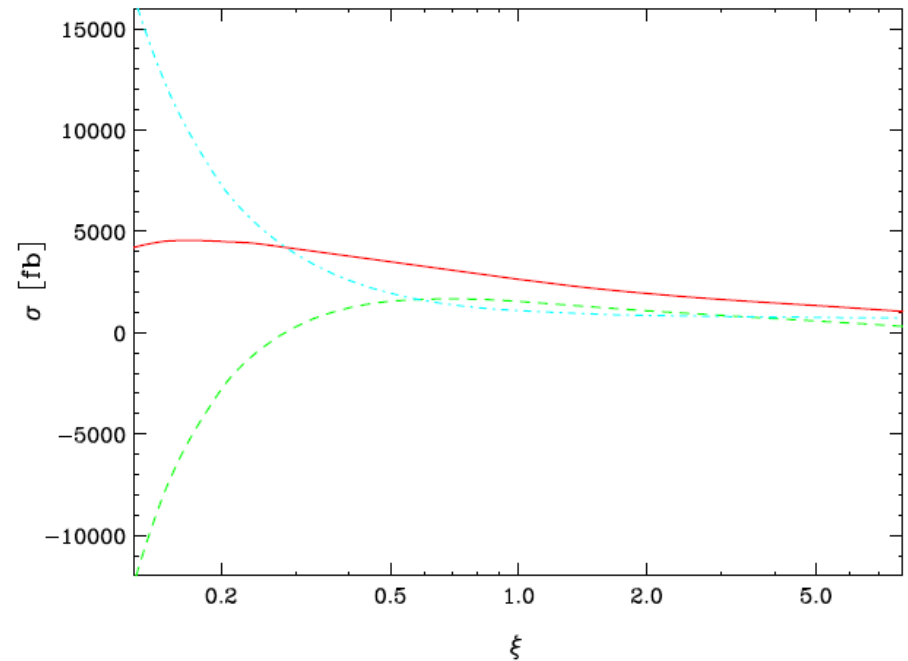
With jet veto of 50 GeV **K = 1.20**

pp \rightarrow 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**

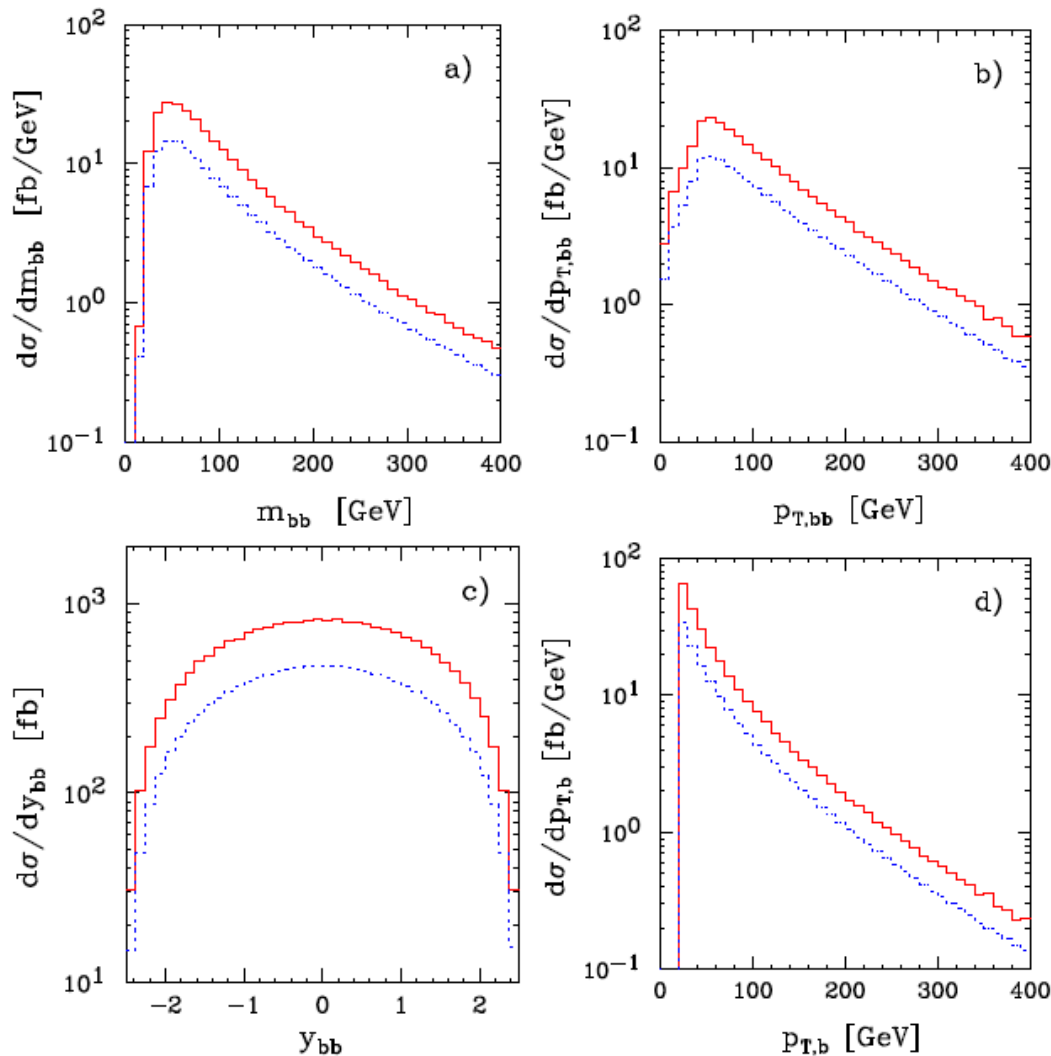


- Scale dependence at **NLO** decomposed into contribution of **Virtual Corrections** & **Real Radiation**

pp \rightarrow 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

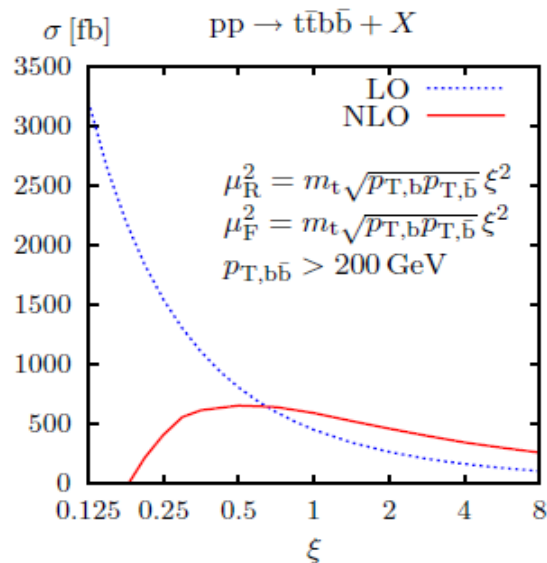
- Relatively small variation compared to the size but shape change important

Highly boosted b-quark pairs

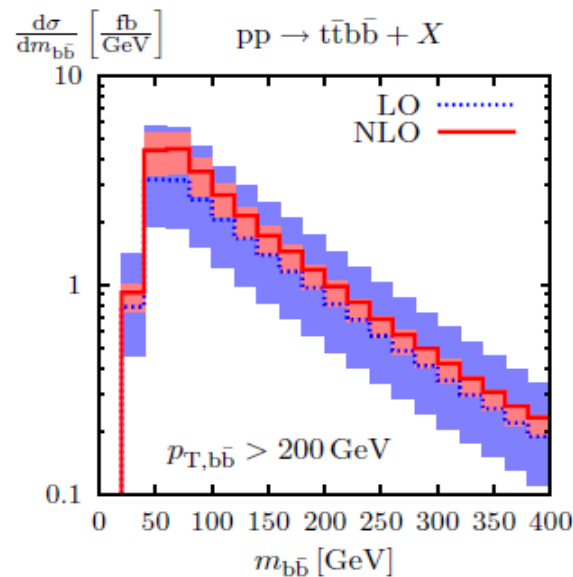
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini '10

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

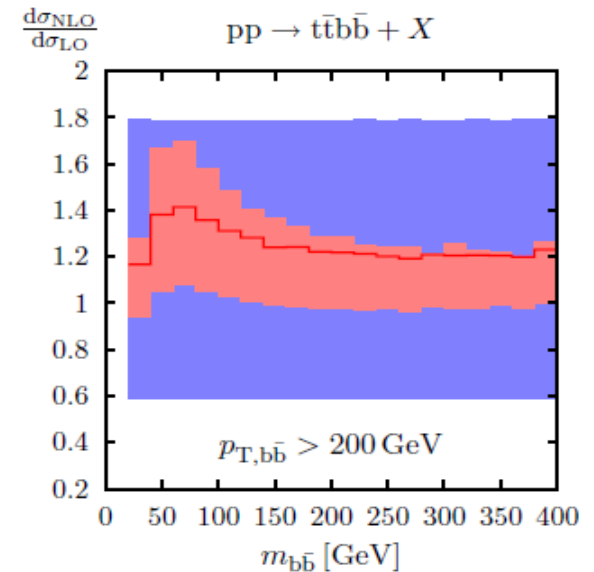
Setup	$m_{b\bar{b},\text{cut}}$	$p_{T,b\bar{b},\text{cut}}$	$p_{\text{jet,veto}}$	$p_{T,b,\text{cut}}$	$y_{b,\text{cut}}$	σ_{LO}	σ_{NLO}	K
I	100	-	-	20	2.5	786.3(2) ^{+78%} _{-41%}	978(3) ^{+13%} _{-21%}	1.24
II	-	200	-	20	2.5	451.8(2) ^{+79%} _{-41%}	592(4) ^{+13%} _{-22%}	1.31
III	100	-	100	20	2.5	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



$m_{b\bar{b}}$ distribution



Dynamic K-factor

pp \rightarrow ttjj @ LHC



$$\sqrt{s} = 14 \text{ TeV}$$

$$p_T(j) > 50 \text{ GeV}$$

$$|y(j)| < 4.5$$

$$\Delta R(j,j) > 1.0$$

$$\mu_R = \mu_F = m_{\text{top}}$$

CTEQ6L1, CTEQ6M

k_T algorithm $R = 0.8$

pp → ttjj @ LHC

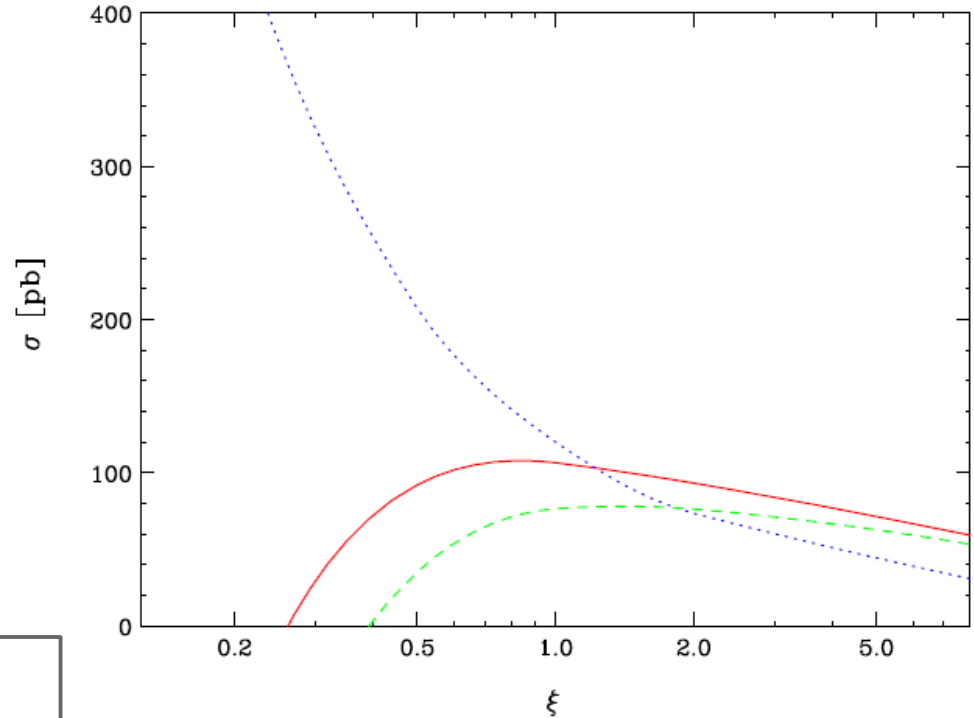
G. Bevilacqua, M. Czakon, C. G. Papadopoulos, M. Worek '10

PROCESS	σ^{LO} [pb]	CONTRIBUTION
$pp \rightarrow t\bar{t}jj$	120.17(8)	100 %
$qg \rightarrow t\bar{t}qg$	56.59(5)	47.1 %
$gg \rightarrow t\bar{t}gg$	52.70(6)	43.8 %
$qq' \rightarrow t\bar{t}qq', q\bar{q} \rightarrow t\bar{t}q'\bar{q}'$	7.475(8)	6.2 %
$gg \rightarrow t\bar{t}q\bar{q}$	1.981(3)	1.6 %
$q\bar{q} \rightarrow t\bar{t}gg$	1.429(1)	1.2 %

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

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

K factor of **K = 0.89** (**K = 0.64**)
 → Negative shift of **11%** (**36%**)

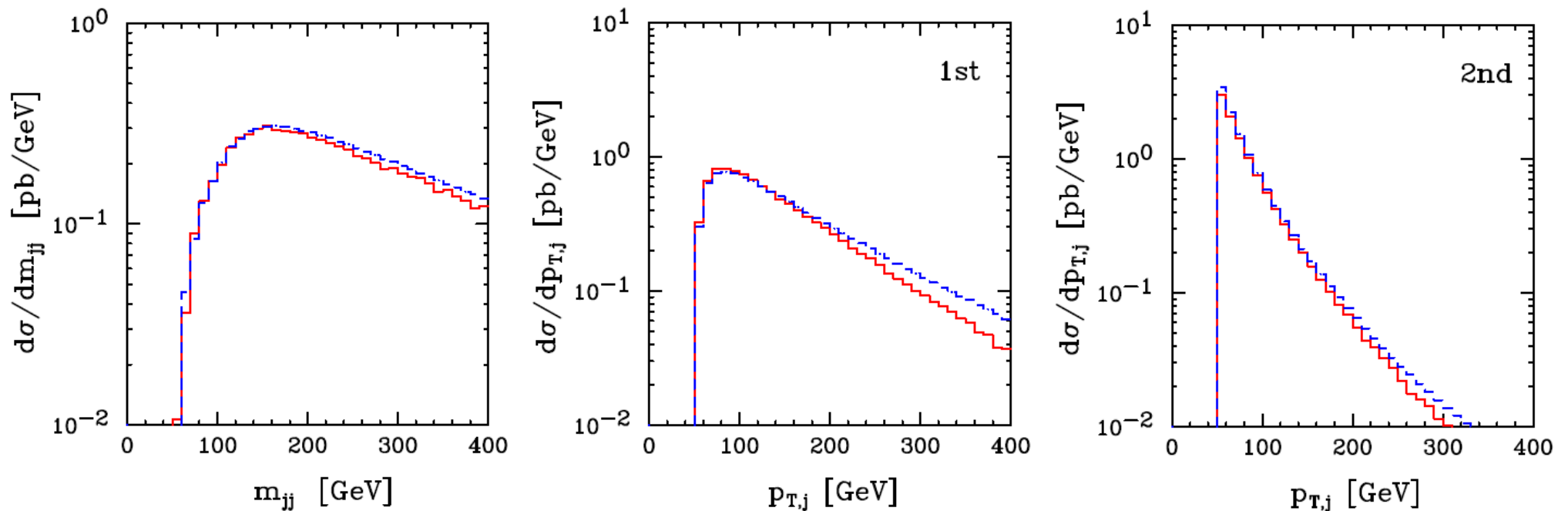


Scale dependence reduced:
72% at **LO** → **13%** at **NLO**
54% at **NLO with jet Veto** of 50 GeV

$$m_{\text{top}} = 172.6 \text{ GeV}$$

pp \rightarrow 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 high 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**

Summary & Outlook



- Automated approach **HELAC-NLO**

→ **HELAC-PHEGAS, HELAC-1LOOP, CUTTOOLS, HELAC-DIPOLES, ONELOOP**

- First results have already been presented:

- ♣ **pp** → **ttbb** (2 independent groups)

- ♣ **pp** → **ttH** → **ttbb**

- ♣ **pp** → **ttjj**

- Reproduce results of previous study of **pp** → **ttj** $\sigma_{\text{HELAC_NLO}} = 376.6(6) \text{ pb}$ [$\sigma = 376.2(6) \text{ pb}$]

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

- More 2 → 4 processes in preparation

- Phenomenological study: fat jets @ NLO & **pp** → **ttjj** @ NLO

- Next big step – matching NLO fixed order to parton shower

- Other general & automatic systems: **BLACKHAT/SHERPA, ROCKET/MCFM, GOLEM, ...**