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

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Outline

- General Motivation for NLO
- (Some) Motivation on the pp → ttbb & pp → ttjj process
- HELAC-NLO
- Results for pp → ttbb
- Results for pp → ttjj
- Summary & Outlook

HELAC-NLO Group:

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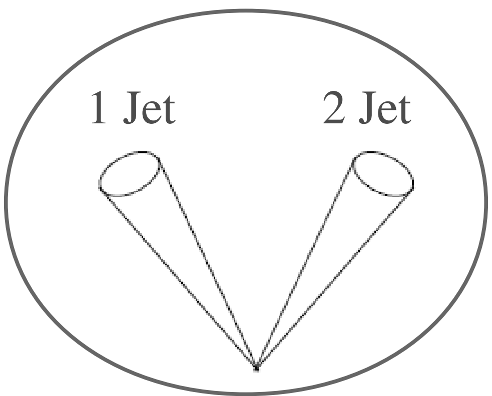
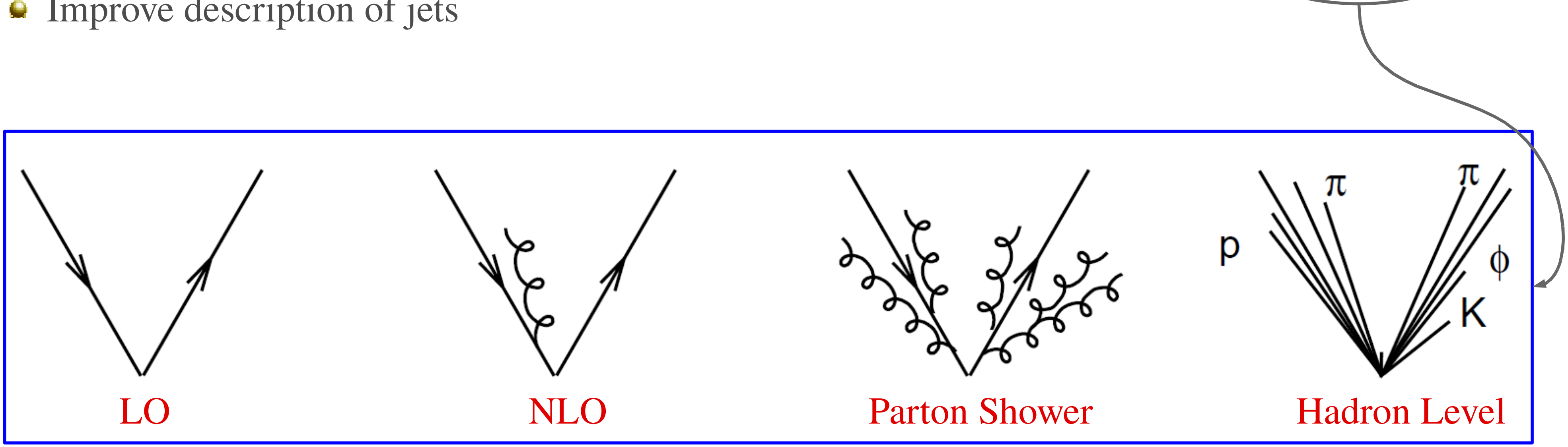
General Motivation for NLO

- 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, ...
- Sometimes dynamical scales seem to work better for some observables
- How to know that the scale is chosen properly ?
- Improve description of jets





(Some) Motivation on the pp → ttbb (ttjj)

- Background to **ttH** production where the Higgs boson decays into a bb pair

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

- Early studies at ATLAS and CMS suggested discovery potential
- Analyses with realistic backgrounds show problems if backgrounds not controlled

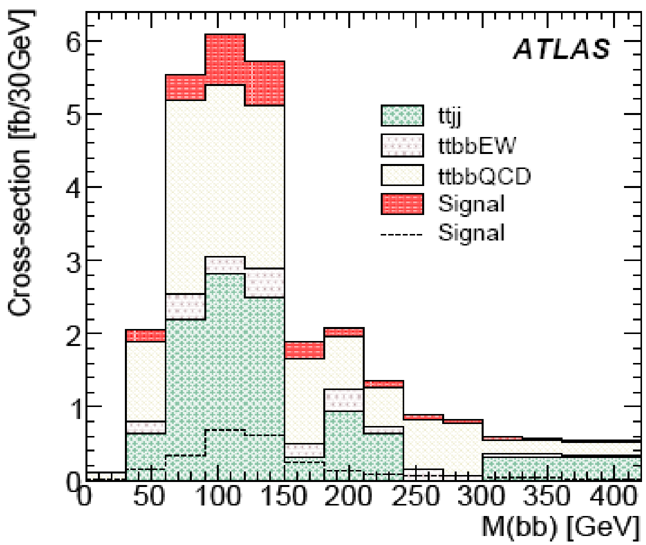
- **ttjj** → 'reducibe' background

- **ttbb** → 'irreducibe' background

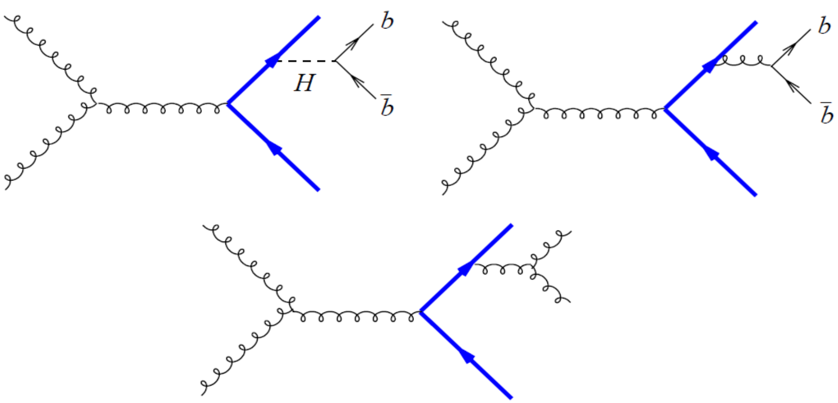
- **Problem:** misassociation of b-tagged jets to the orginal partons

- **ttH** gives unique access to top Yukawa coupling & to bottom Yukawa coupling

ATLAS TDR, CERN-OPEN-2008-020



- Reconstructed mass distribution



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, 2001; L. Reina, S. Dawson 2001, S. Dawson, L.H. Orr, L. Reina, D. Wackeroth, 2003
- NLO QCD corrections to ttH → ttbb — G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, C.G. Papadopoulos, R. Pittau, M. Worek, 2010 (Les Houches 2009)
- NLO QCD corrections to ttbb — A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini, 2008, 2009, 2010; G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek, 2009
- NLO QCD corrections to ttjj — G. Bevilacqua, M. Czakon, C.G. Papadopoulos, M. Worek, 2010

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

Great Needs of Experimentalists

- Updated NLO wishlist, Les Houches 2009
- Despite removal of many processes, the list is very ambitious
- Cross-sections experimentalists would like to know at NLO, 2004

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

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

HELAC-NLO

HELAC-PHEGAS

A. Kanaki, C. G. Papadopoulos, 2000
C. G. Papadopoulos, 2001
A. Cafarella, C. G. Papadopoulos, M. Worek, 2009

→ 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, 2009

→ Evaluation of one-loop n particle amplitude

CUTTOOLS

G. Ossola, C. G. Papadopoulos, R. Pittau, 2007, 2008
P. Draggiotis, M. V. Garzelli, C. G. Papadopoulos, R. Pittau, 2009

→ Determination of coefficients via OPP reduction method together with rational part
→ http://www.ugr.es/~pittau/CutTools

ONELOOP

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

HELAC-DIPOLES

M. Czakon, C. G. Papadopoulos, M. Worek, 2009

→ Catani-Seymour dipole subtraction for massless and massive cases
→ Phase space integration of subtracted real radiation and integrated dipoles
→ Extended for arbitrary polarizations
→ http://helac-phegas.web.cern.ch/helac-phegas/

pp → ttbb @ LHC

$\sqrt{s}$ = 14 TeV
$p_T(j) > 25$ 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

Results for pp → ttbb @ LHC

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

Permille level agreement!

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

m_{top} = 172.6 GeV

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

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

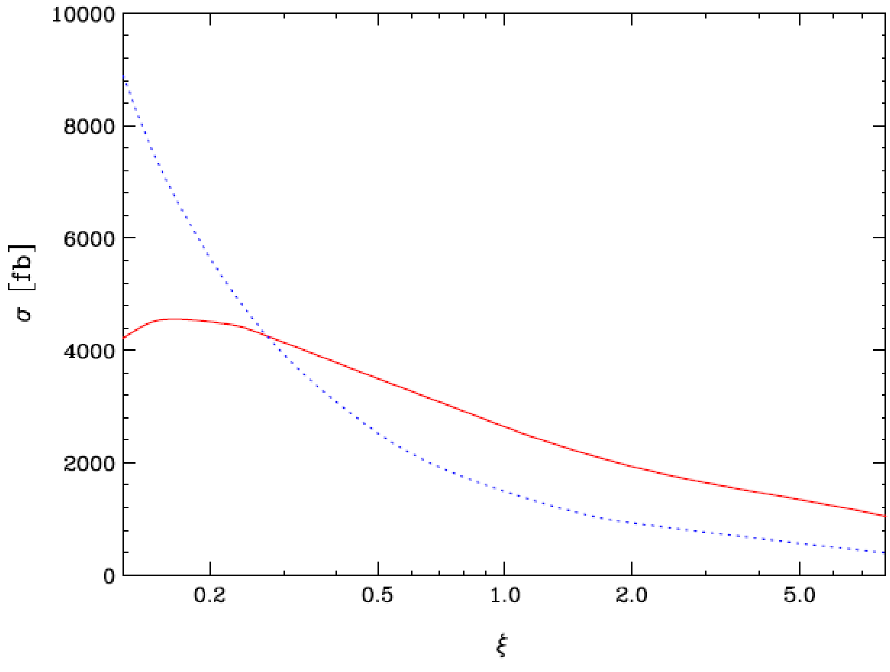
$$\sigma^{\rm NLO}_{t\bar{t}b\bar{b}} = 2636 \begin{array}{l} +862\ (33\%) \\ -703\ (27\%) \end{array} \ {\rm fb}$$

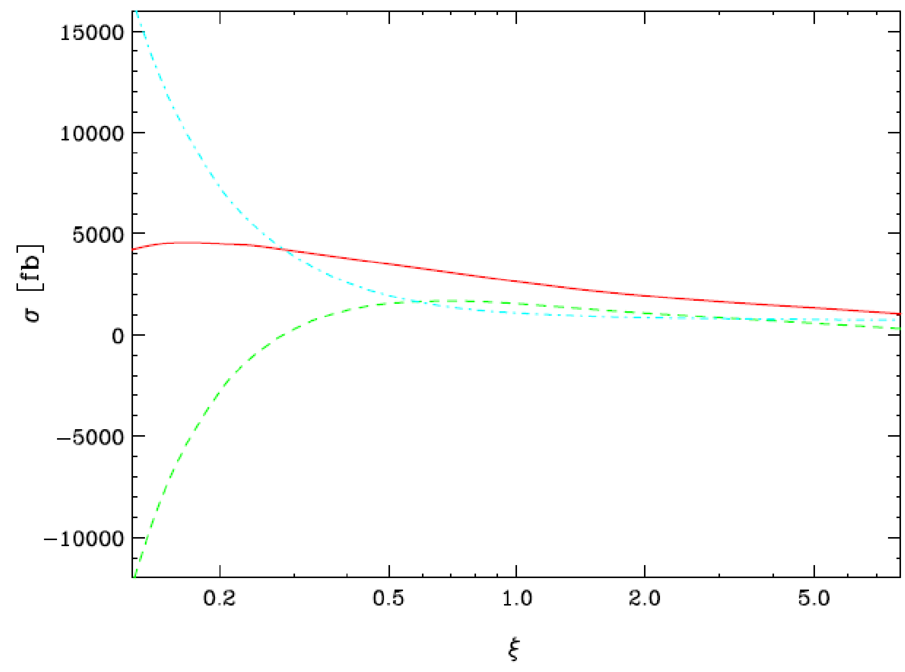
Scale dependence reduced:
70% (LO) → **33%** (NLO)

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

Scale Dependence for pp → ttbb @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek, 2009

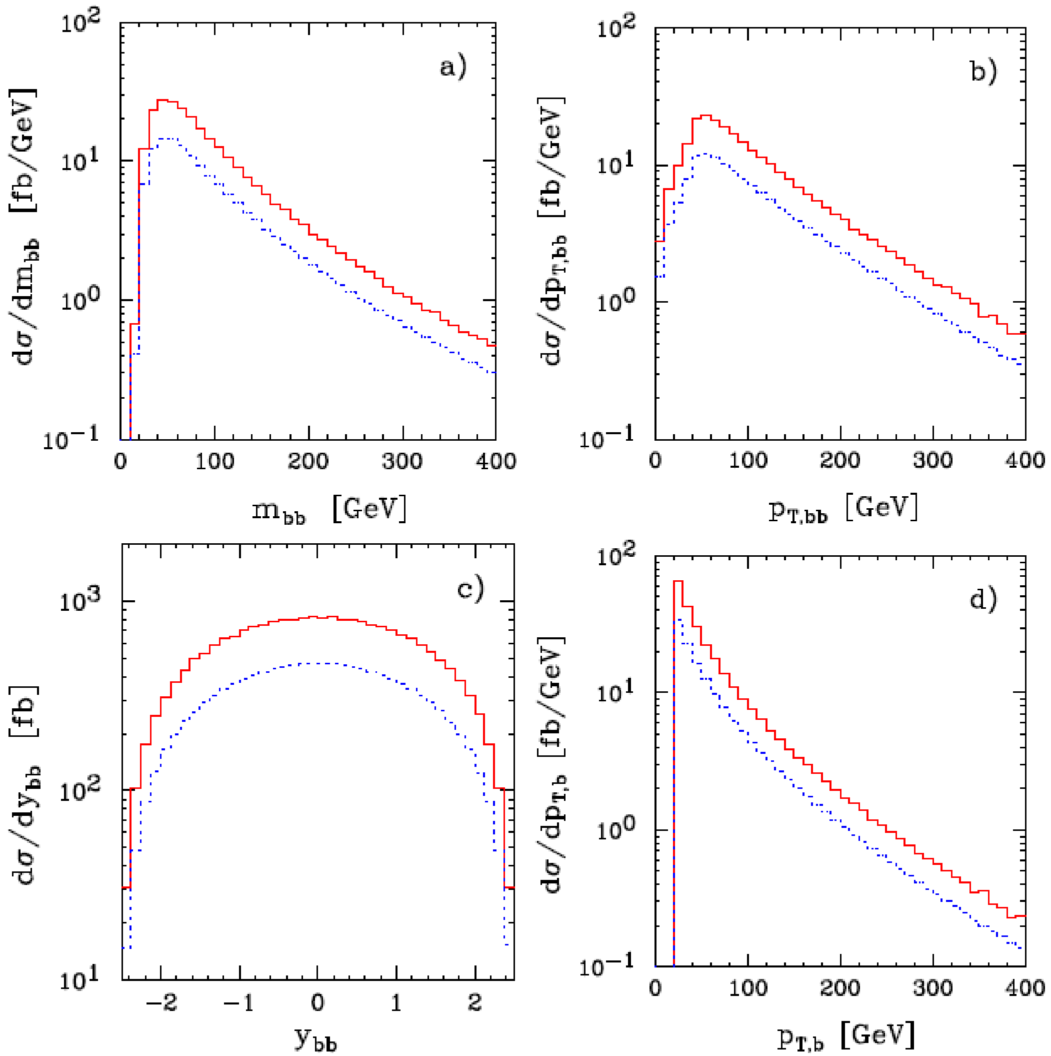




- Varying scale up or down by a factor 2 changes cross section by **70%** at **LO** and by **33%** at **NLO**
- Scale dependence at **NLO** decomposed into contribution of **Virtual Corrections** & **Real Radiation**

Distributions for pp → ttbb @ LHC

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek, 2009



- b-jet pair kinematics

→ Invariant mass distribution
→ Transverse momentum
→ Rapidity distribution

- single b-jet kinematics

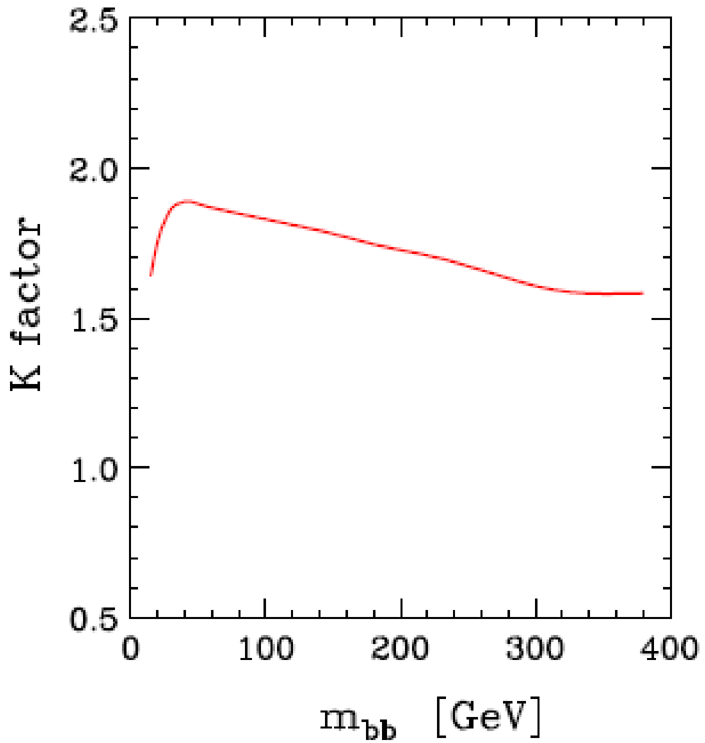
→ Transverse momentum

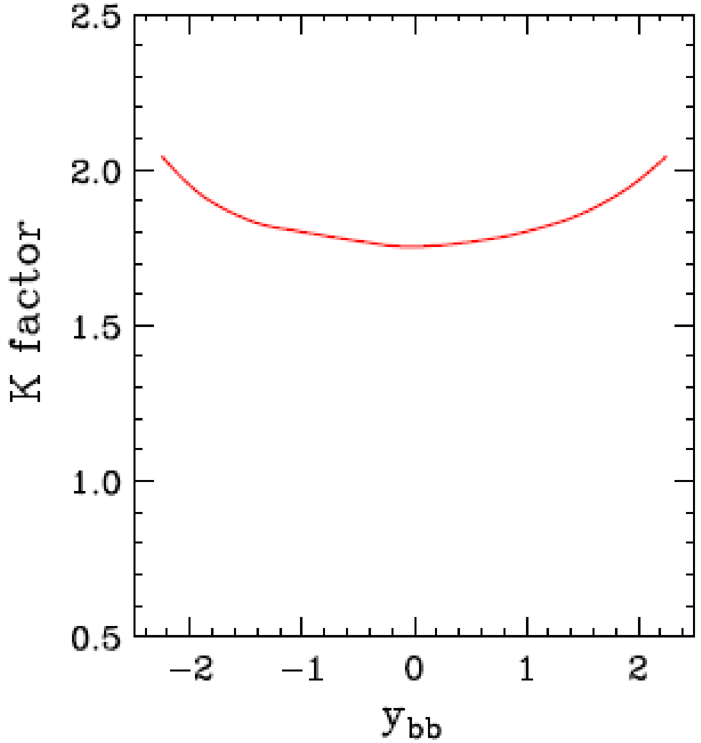
- **LO** & **NLO**
- Large corrections, relatively constant

Dynamical K-factors for pp → ttbb @ LHC

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

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau, M. Worek, 2009





$$K(m_{b\bar{b}}) = \frac{d\sigma^{NLO}/dm_{b\bar{b}}}{d\sigma^{LO}/dm_{b\bar{b}}}$$

$$K(y_{b\bar{b}}) = \frac{d\sigma^{NLO}/dy_{b\bar{b}}}{d\sigma^{LO}/dy_{b\bar{b}}}$$

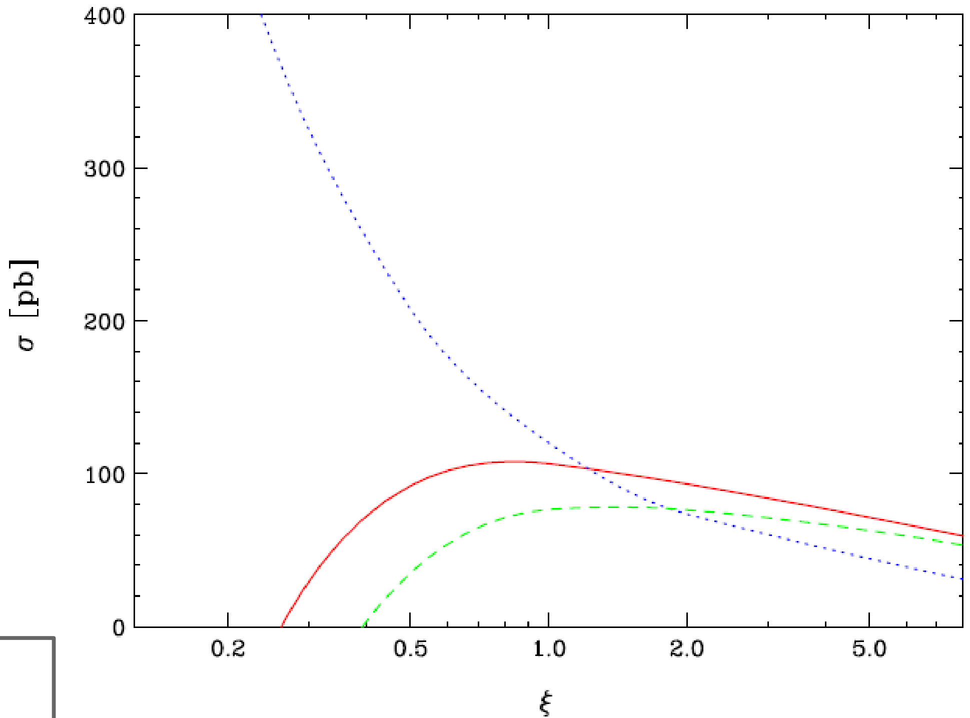
$pp \to t\bar{t}jj$ @ LHC

$\sqrt{s} = 14$ 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

Results for pp → ttjj @ LHC

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

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 %



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

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

Scale dependence reduced:

72% LO → 13% NLO

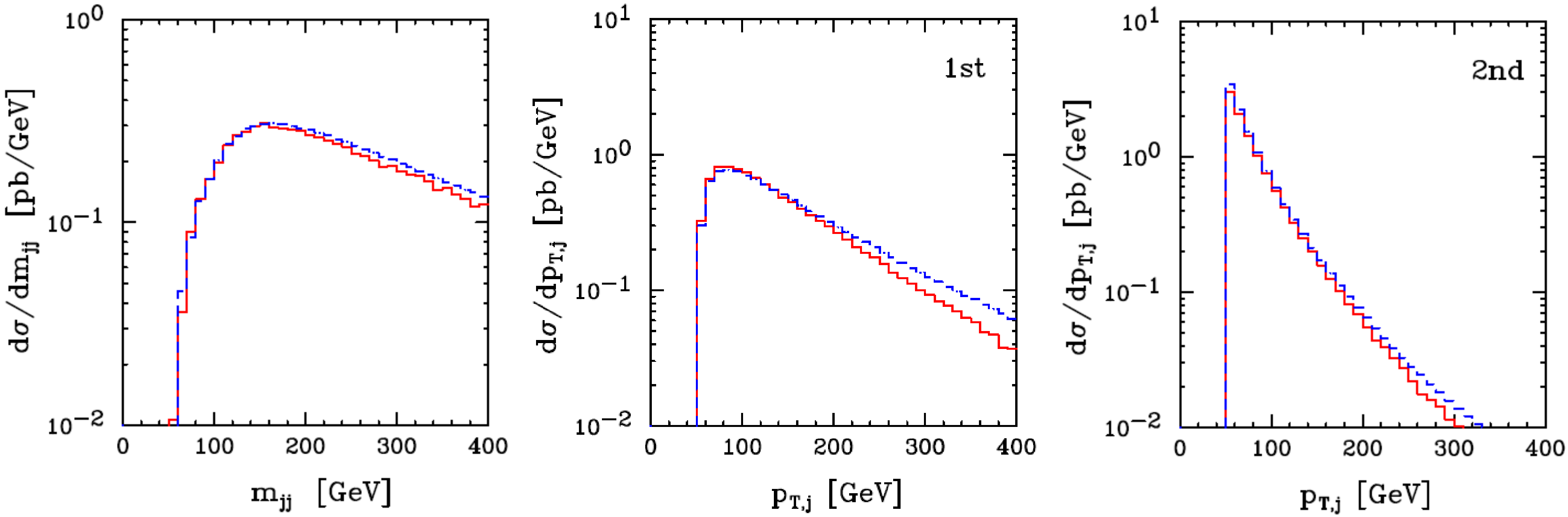
54% NLO with Jet Veto

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

m_{top} = 172.6 GeV

Distributions for pp → ttjj @ LHC

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



invariant mass of 2j system
→ size of the corrections transmitted to the most relevant distribution

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 (by 2 independent groups) & pp → ttjj

- Reproduce results of previous study of pp → ttj $\boldsymbol{\sigma}_{\text{HELAC\_NLO}}$ **= 376.6(6) pb** [σ = 376.2(6) pb]

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

- More 2 → 4 processes in preparation (finish off NLO wishlist)

- Phenomenological study for ttH → ttbb process with pp → ttbb, pp → ttjj backgrounds

- Present a much wider study for pp → ttj & pp → ttjj

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

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