BERGISCHE UNIVERSITÄT WUPPERTAL

NLO QCD corrections to pp → ttbb

PHYSICS AT THE TERA SCALE Helmholtz Alliance

Malgorzata Worek

Bergische Universität Wuppertal

Outline of the Talk

- Introduction & Motivation
- Real emission: **HELAC-DIPOLES**
- Virtual contributions: **OPP, CUTTOOLS, HELAC-1LOOP, ONELOOP**
- Results
- Summary & Outlook

In collaboration with: G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau

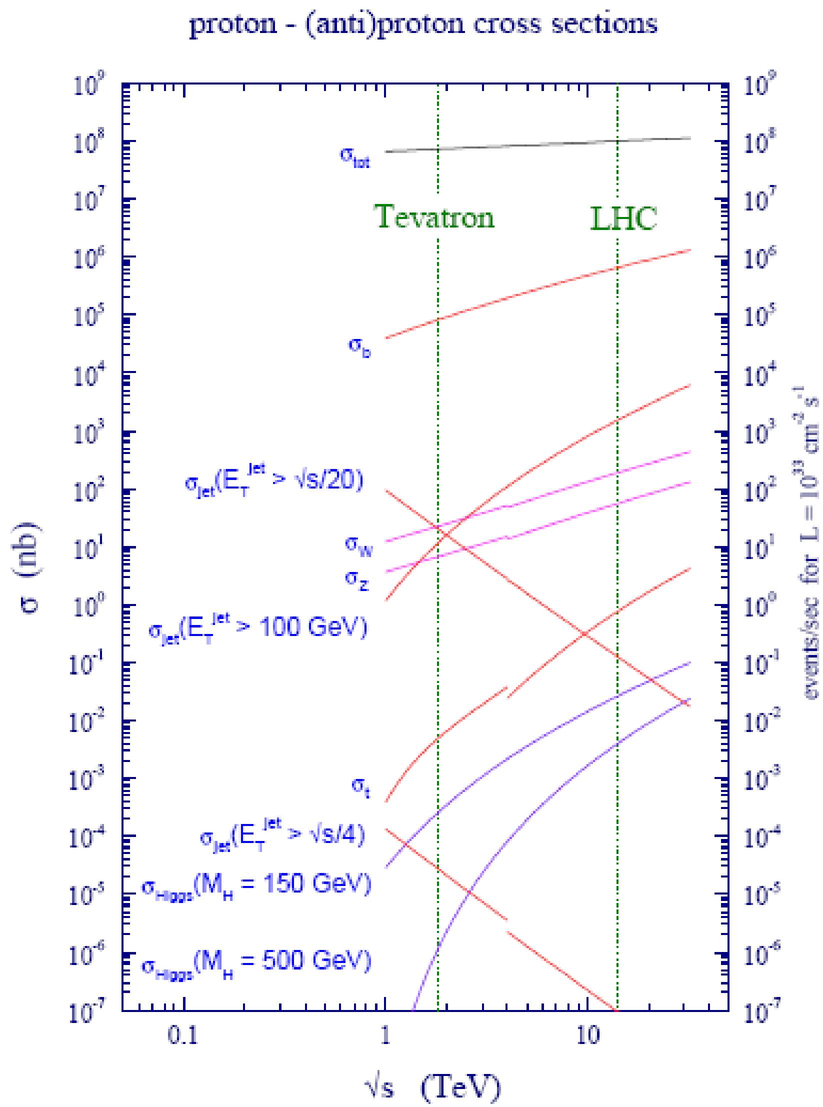
Why NLO

Multi-leg processes at the LHC

- Huge W, Z and top-quark production rates plus multiple jet emission
- Multi-particle signatures with leptons, jets and missing energy
- Backgrounds to Higgs boson(s) and new physics

Benefits of higher order calculations

- Less sensitivity to unphysical input scales
  - ⇨ LO up to a factor of 2, NLO 10%-20%
- First predictive normalisation of observables
- Improved shape of distributions
- Improve description of jets



Motivation

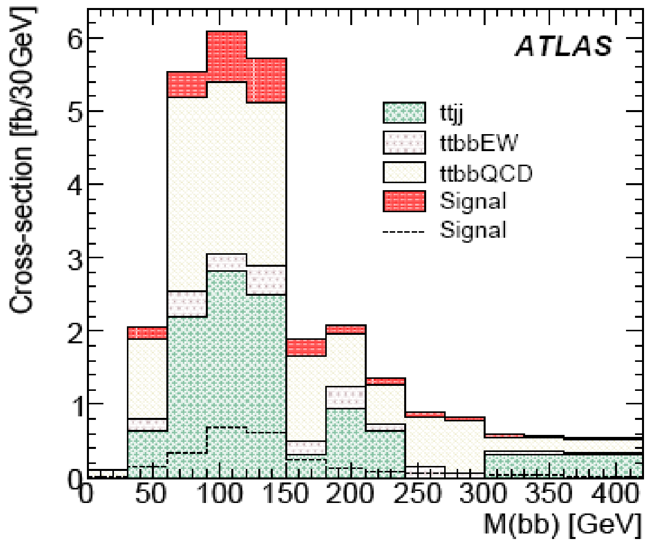
On the experimental side

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

$$m_H \leqslant 135\ GeV$$

- Early studies at ATLAS and CMS suggested discovery potential
- Analyses with more realistic backgrounds show problems if background from **ttbb** and **ttjj** not controlled very well
- **ttjj** ⇨ 'reducible' background
- **ttbb** ⇨ 'irreducible' background
- **Problem:** misassociation of b-tagged jets to the orginal partons

ATLAS TDR, CERN-OPEN-2008-020



- Reconstructed mass distribution
- All samples, contributions stacked
- Signal contribution also shown separately at the bottom.

Motivation

On the theoretical side

- NLO corrections to $2 \rightarrow 4$ processes current technical frontier
- The complexity of such calculations triggered creation of special experimenters' wishlists
- ttbb production ranges among the most wanted candidates

- NLO QCD corrections to ttH — Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01
  Reina, Dawson '01 & Dawson, Orr, Reina, Wackeroth '03

- NLO QCD corrections to ttbb — Bredenstein, Denner, Dittmaier, Pozzorini '08 & '09

- Confirm published results
- Demonstrate power of system based on **HELAC-PHEGAS**, **HELAC-1LOOP**, **CUTTOOLS**, **ONELOOP**, **HELAC-DIPOLES** in realistic computation with 6 external legs and massive partons

Real radiation

HELAC-DIPOLES

http://helac-phegas.web.cern.ch/helac-phegas/

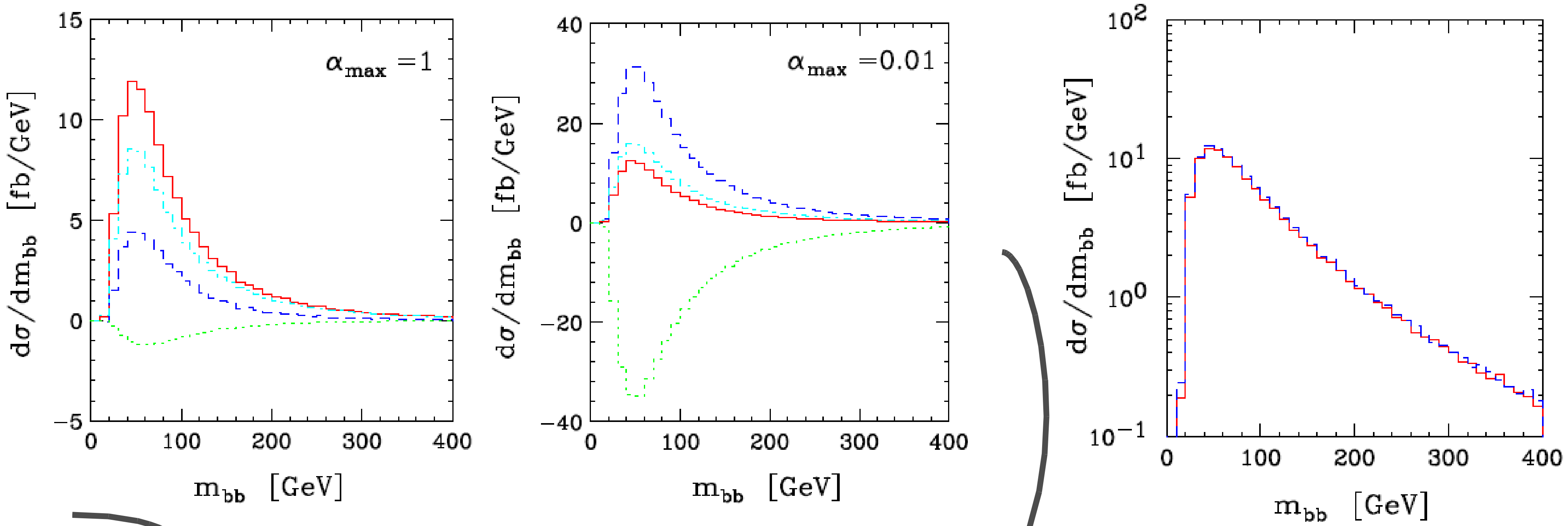
- Complete, publicly available automatic implementation of Catani-Seymour dipole subtraction
  - ⇒ phase space integration of subtracted real radiation and integrated dipoles in both massless and massive cases — Catani, Seymour '97 & Catani, Dittmaier, Seymour, Trocsanyi '02
- Extended for arbitrary polarizations — Czakon, Papadopoulos, Worek '09
  - ⇒ Monte Carlo over polarization states of external particles
- Phase space restriction on the dipole phase space $\alpha_{max} \in \;]0,1]$

  Nagy, Trocsanyi '99 & Nagy '02
  Campbell, Ellis, Tramontano '04
  Campbell, Tramontano '05
  Czakon, Worek, Papadopoulos '09

  - ⇒ Cuts off dipole function for phase space regions away from singularity
  - ⇒ Less dipoles subtraction terms needed per event
  - ⇒ Increased numerical stability by decreasing size of dipole phase space
  - ⇒ Reduced missed binning problem
  - ⇒ Large cancellations between dipoles subtracted real radiation and integrated dipoles

Cutoff Dependence

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Full result
Dipole subtracted real emission
K + P operators
I operator

Internal check ⇒ Cutoff independence in distributions

Virtual corrections

- One-loop n particle amplitude

$$A = \sum_{I\in\{1,2,\ldots,n\}} \int \frac{\mu^{4-d} d^d \bar{q}}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i\in I} \bar{D}_i(\bar{q})} \qquad \bar{D}_i(\bar{q}) = (\bar{q}+p_i)^2 - m_i^2, \quad i=1,2,\ldots,n$$

$$A = \sum_i d_i\, Box_i + \sum_i c_i\, Triangle_i + \sum_i b_i\, Bubble_i + \sum_i a_i\, Tadpole_i + R$$

- Amplitude can be expressed in basis of known integrals such 4-, 3-, 2-, 1-point scalar integrals

- In order to calculate one loop amplitude three main building blocks are needed:

  - ⇨ Evaluation of numerator function N(q) - **HELAC-1LOOP** van Hameren, Papadopoulos, Pittau '09
  - ⇨ Determination of coefficients via reduction method - **OPP, CUTTOOLS** Ossola, Papadopoulos, Pittau '07 & '08
  - ⇨ Evaluation of scalar functions – **ONELOOP** http://annapurna.ifj.edu.pl/~hameren/

OPP

- Reduction at integrand level – OPP method implemented in **CutTools**
- Solved using method resembling generalized unitarity – computing numerator functions for specific values of loop momenta

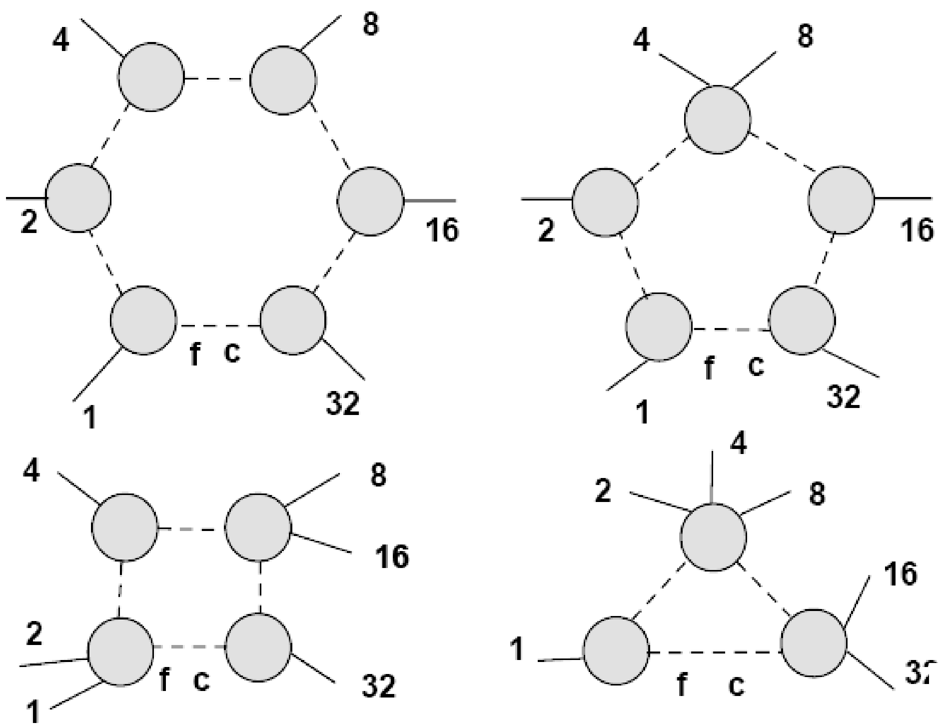
$$D_i(q) = 0, \qquad \text{for} \quad i = 0, \ldots, M-1$$

- Customary to refer to these equations as quadruple (M=4), triple (M=3), double (M=2) and single (M=1) cuts

$$\begin{aligned} N(q) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\ & + \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\ & + \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\ & + \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i \\ & + \tilde{P}(q) \prod_{i}^{m-1} D_i \,. \end{aligned}$$

Ossola, Papadopoulos, Pittau '07 & '08

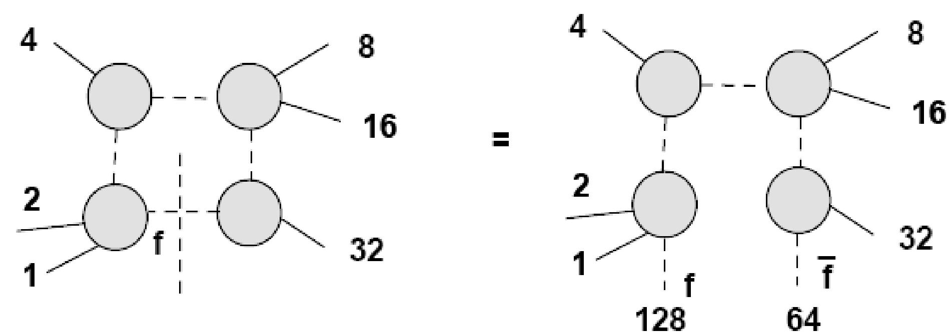
HELAC-1LOOP



Typical collection of possible contributions

van Hameren, Papadopoulos, Pittau '09

- Calculating N(q) for specific loop momenta
- Possibility to use tree level amplitudes
- Collecting all contributions with given loop propagator
- Calculated as part of tree level amplitude with n+2 particles in 4 dimensions



Efficiency & Precision

- Monte Carlo over color
- Full color available!
- 0.5 seconds per event
- Reweighting

$$\sigma_{ab}^{LO+V} = \int dx_1 dx_2 d\Phi_m f_a(x_1) f_b(x_2) |\mathcal{M}|^2 \left(1 + \frac{\mathcal{M}\mathcal{L}^* + \mathcal{M}^*\mathcal{L}}{|\mathcal{M}|^2}\right)$$

- Much less points to evaluate (200 000 for permille accuracy in our case)
- Based on smothness argument
- Avoids numerical instabilities
- Gauge check for each phase space point to certify precision

Virtual corrections

Procedure to calculate one-loop amplitude fully automatically

- Construction of all numerator functions using **HELAC-1LOOP**, all flavours within SM can be included either as external or internal (loop) momenta, all particles can have arbitrary masses
- Each numerator function reduced using **CUTTOOLS**, part of rational term is obtained
- N(q) calculated for particular q given by **CUTTOOLS** via **HELAC-1LOOP**
- Rational term with special Feynman rules

  Draggiotis, Garzelli, Papadopoulos, Pittau '09
  Garzelli, Malamos, Pittau '09

- Construction of all UV counter term contributions needed to renormalize amplitude

Comparison

- Cross sections for pp → ttbb + X at the LHC at LO and NLO
- Scale choice $\mu_F = \mu_R = m_t$

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09
Bredenstein, Denner, Dittmaier, Pozzorini '08 & '09

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]
$q\bar{q} \to t\bar{t}b\bar{b}$	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)

- **K = 1.77**, reduced to **K = 1.2** by introducing veto on extra jet
- For qq initial state **K = 1.03** only

Scale Dependence

- Scale dependence at the LHC for $\mu_R = \mu_F = \xi \cdot m_t$ at LO & NLO

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

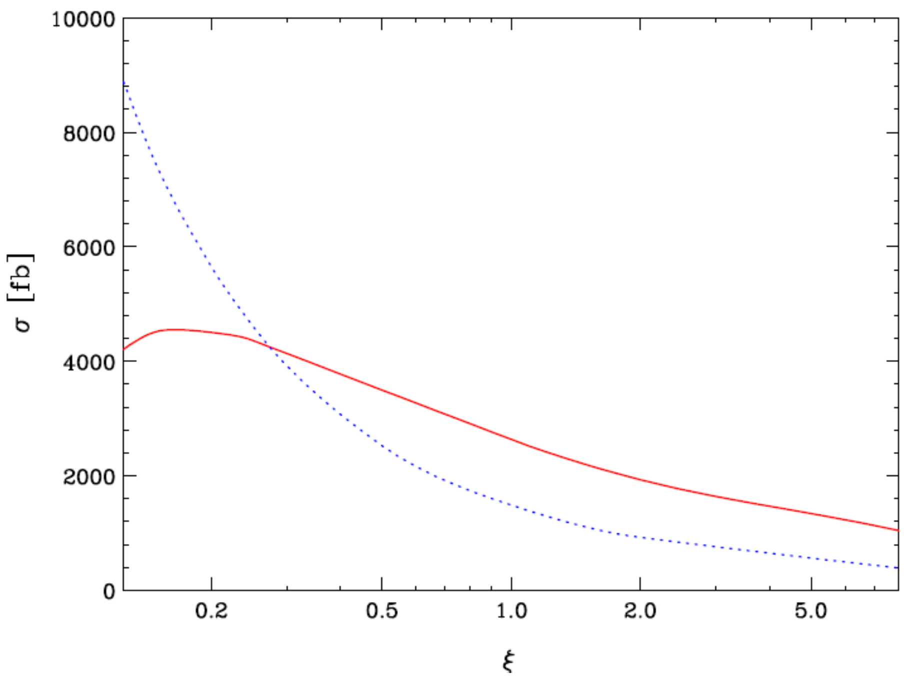
$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
$\sigma^{\rm LO}$ [fb]	8885(36)	2526(10)	1489.2(0.9)	923.4(3.8)	388.8(1.4)
$\sigma^{\rm NLO}$ [fb]	4213(65)	3498(11)	2636(3)	1933.0(3.8)	1044.7(1.7)

$$\sigma^{\rm LO}_{t\bar{t}b\bar{b}}({\rm LHC}, m_t = 176.2 \text{ GeV}, \text{CTEQ6L1}) = 1489.2 \begin{array}{l} +1036.8\ (70\%) \\ -\ \ 565.8\ (38\%) \end{array} \text{ fb}$$

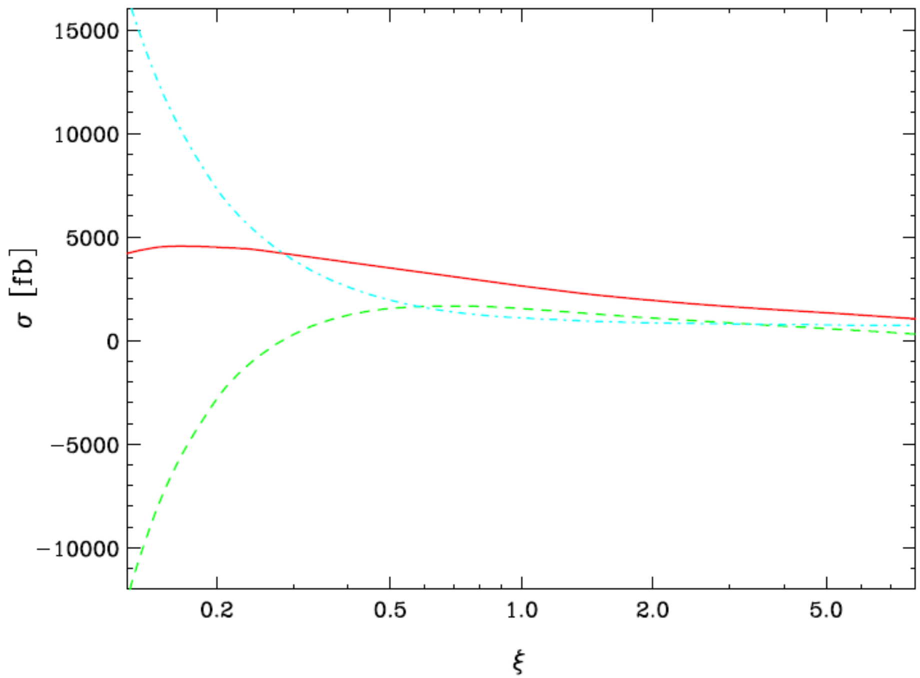
$$\sigma^{\rm NLO}_{t\bar{t}b\bar{b}}({\rm LHC}, m_t = 176.2 \text{ GeV}, \text{CTEQ6M}) = 2636 \begin{array}{l} +862\ (33\%) \\ -703\ (27\%) \end{array} \text{ fb} .$$

- Varying scale up or down by a factor 2 changes cross section by **70%** in LO & **33%** in NLO

Scale Dependence

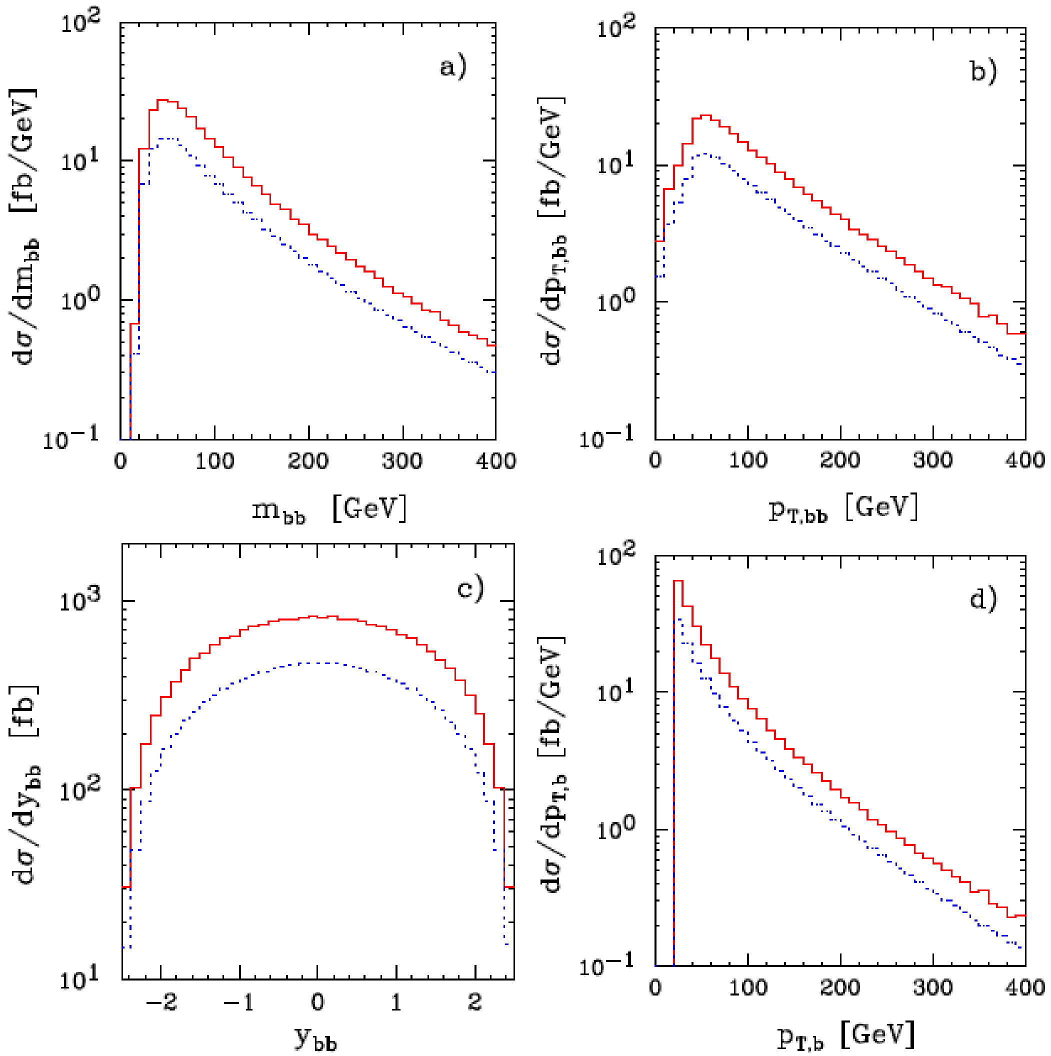


Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



LO
NLO
virtual corrections
real radiation

Distributions



Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

- Differential cross sections at the LHC for pp → ttbb + X

- Invariant mass distribution of bb pair
- Transverse momentum of bb pair
- Rapidity distribution of bb pair
- Transverse momentum of b quark

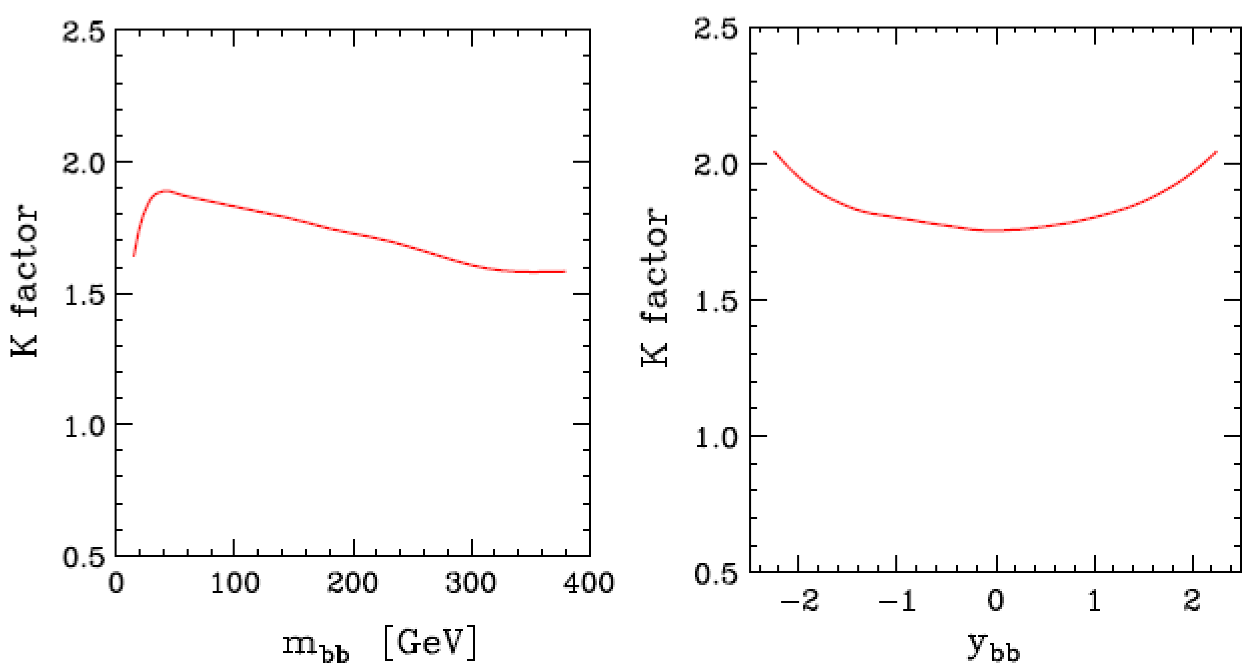
- LO
- NLO

- All distributions for $\alpha_{max} = 0.01$
- Large corrections, relatively constant

Dynamical K-factor

- Ratio of NLO and LO distributions at the LHC for pp → ttbb + X
- Relatively small variation when compared with their size

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



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

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

Summary & Outlook

- NLO cross sections and distributions display reduction in renormalization- and factorization-scale dependence compared to quantities calculated at LO
- Solution: automated approaches build around **HELAC-PHEGAS** **HELAC-1LOOP**, **CUTTOOLS** and **HELAC-DIPOLES, ONELOOP**
- Promising and feasible
- First results have been obtained
- More 2 $\rightarrow$ 4 processes in preparation

Outlook

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