BERGISCHE UNIVERSITÄT WUPPERTAL

Automatic LO and NLO calculations with HELAC-PHEGAS framework

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Malgorzata Worek

Bergische Universität Wuppertal

Monte Carlo Meeting, 4 December 2009, Karlsruhe

Outline of the Talk

- LO + LL: **HELAC-PHEGAS**
- NLO: **HELAC-NLO**
- Real emission: **HELAC-DIPOLES**
- Virtual contributions: **OPP, CUTTOOLS, HELAC-1LOOP, ONELOOP**
- Some Results
- Summary & Outlook

In collaboration with: **M. Czakon** (RWTH Aachen)
A. van Hameren (INP Krakow)
C. G. Papadopoulos (IN Athens)
R. Pittau (University of Granada)
+ 3 postdocs:
G. Bevilacqua (INP Athens)
M.V. Garzelli (University of Granada)
P. Draggiotis (University of Valencia)
+ 2 phd students

LO + LL

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

Features of HELAC-PHEGAS

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

Kanaki, Papadopoulos '00
Papadopoulos '01
Cafarella, Papadopoulos, Worek '09

Flexibility

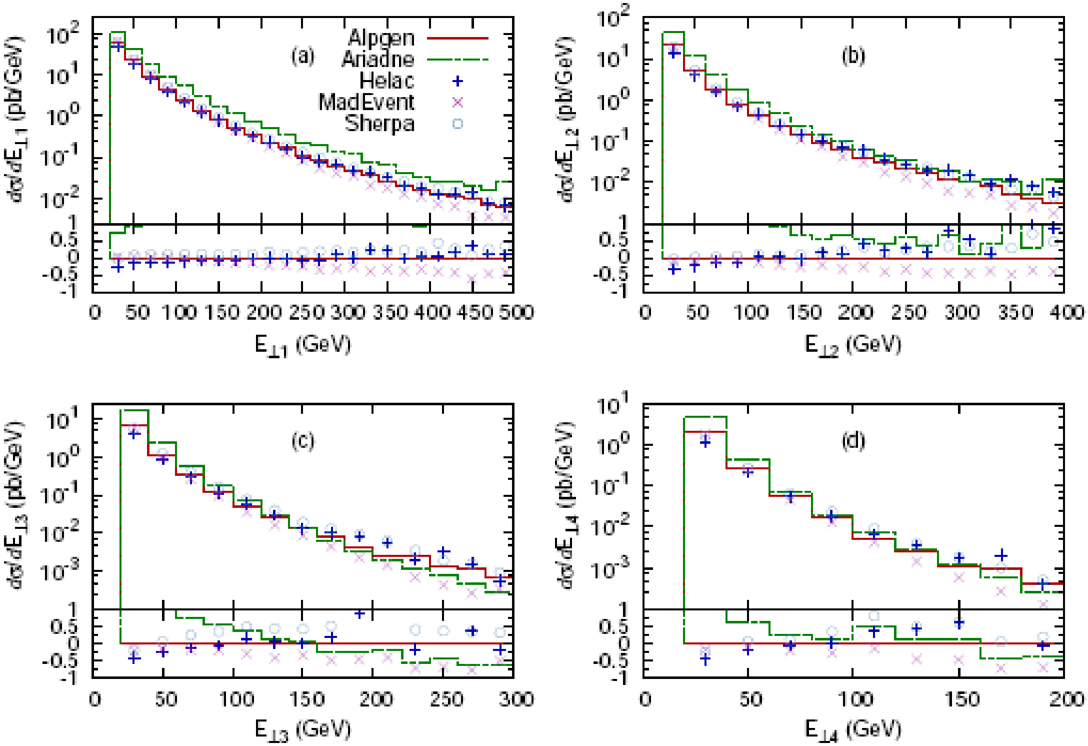
Reliability

Speed

Extensibility

pp → W + jets @ LHC

Inclusive E_T spectra of leading 4 jets



J. Alwall et al. '08

ALPGEN – angular-ordered PS in **HERWIG** with MLM matching

ARIADNE – matrix elements MadGraph, p_T ordered dipole PS with CKKW-L, **PYTHIA**

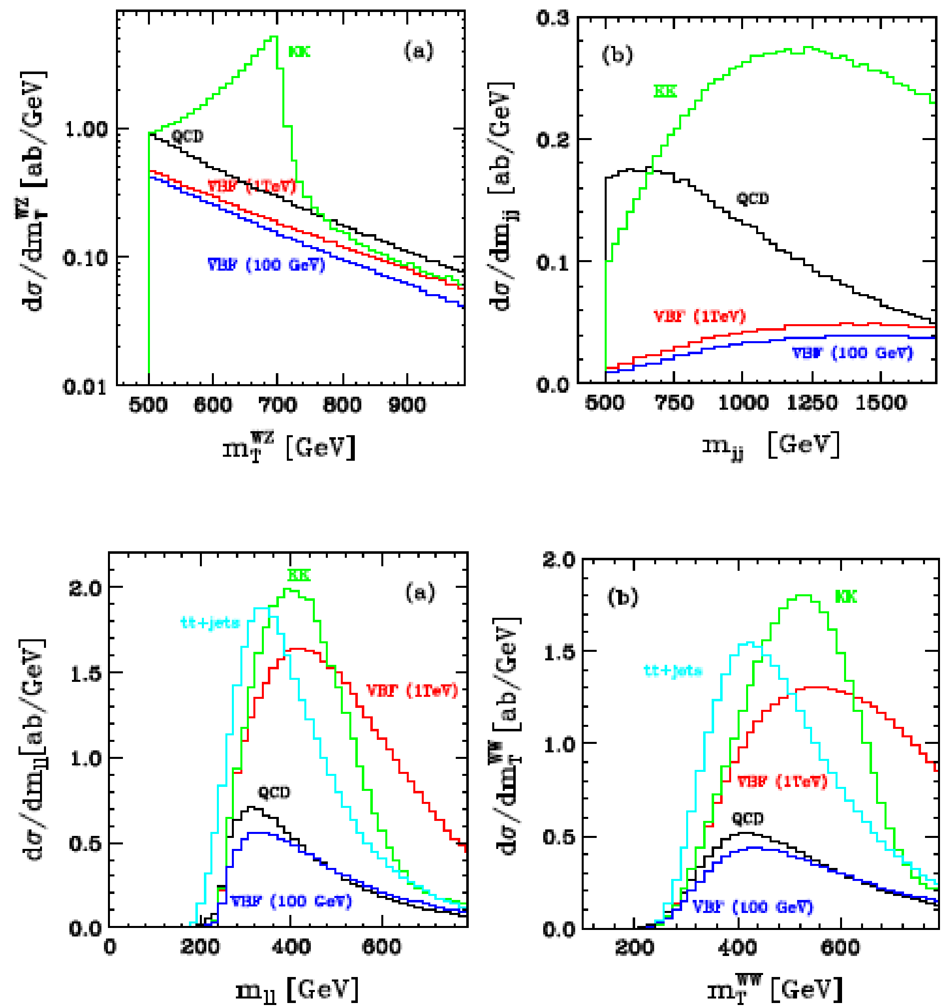
HELAC – mass-ordered PS in **PYTHIA** with MLM matching

MADEVENT – mass-ordered PS in **PYTHIA** with MLM matching

SHERPA – mass-ordered PS with CKKW matching, **PYTHIA**

Backgrounds @ LHC

- $qq \rightarrow W^+W^- qq\,,\ \ qq \rightarrow W^+Z\,qq$
- **VBFNLO** - Warped Higgsless Kaluza-Klein model of narrow spin1 resonances
- **HELAC-PHEGAS** - Most prominent background processes
- Full off-shell and finite width effects for final states with two tagging jets and four leptons
- Double forward jet-tagging techniques
- Dedicated cuts on the observable jets and charged leptons
- Substantial sensitivity to strong interactions in EWSB sector



Englert, Jager, Worek, Zeppenfeld '09

VBFNLO
K. Arnold et al. '09
http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

NLO

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

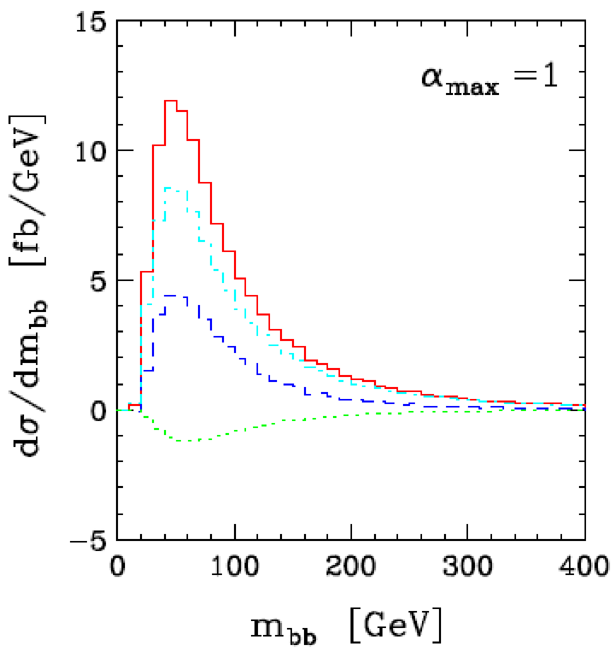
- Phase space restriction on the dipole phase space $\alpha_{max} \in \ ]0,1]$

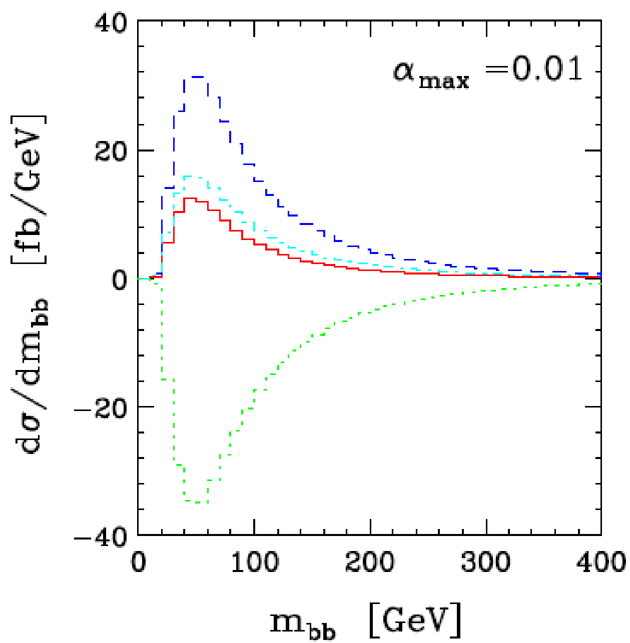
  Nagy, Trocsanyi '99 & Nagy '02
  Campbell, Ellis, Tramontano '04
  Campbell, Tramontano '05
  Czakon, Worek, Papadopoulos '09

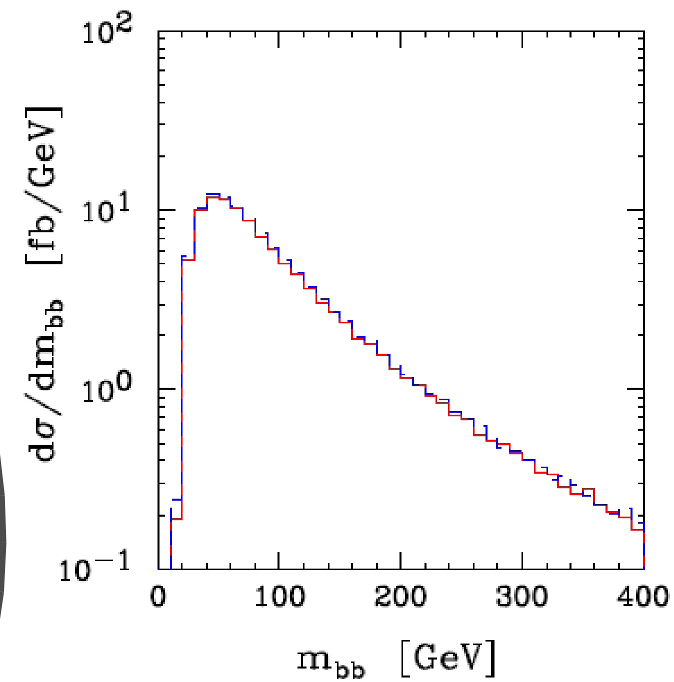
  - ⇒ Cuts off dipole function for phase space regions away from singularity
  - ⇒ Less dipoles subtraction terms needed per event
  - ⇒ Increased numerical stability by decreasing size of dipole phase space
  - ⇒ Reduced missed binning problem
  - ⇒ Large cancellations between dipoles subtracted real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

$$pp \rightarrow t\,\bar{t}\,b\,\bar{b} + X$$

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

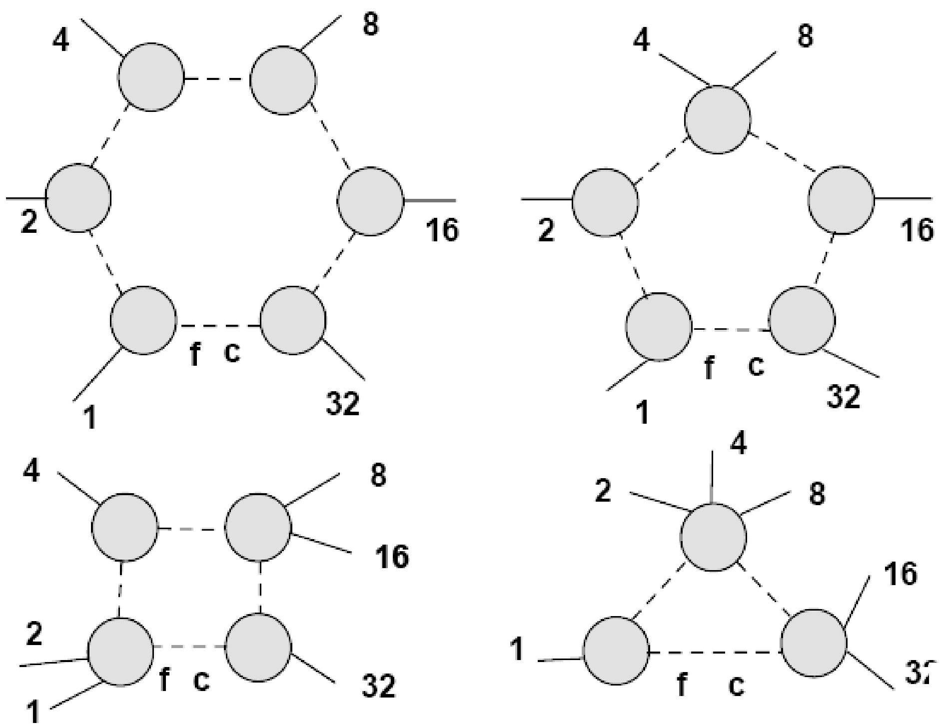
$$D_i(q) = 0, \qquad \text{for} \quad i = 0, \ldots, M-1$$

- 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

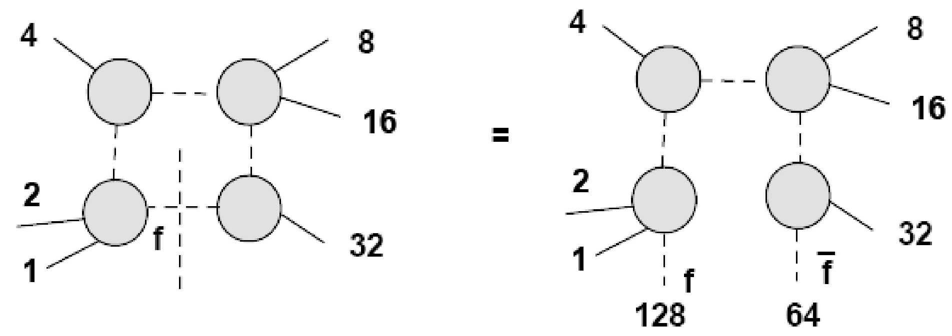
HELAC-1LOOP



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



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

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

Motivation for pp → ttbb

On the theoretical side

- NLO corrections to 2 → 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

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

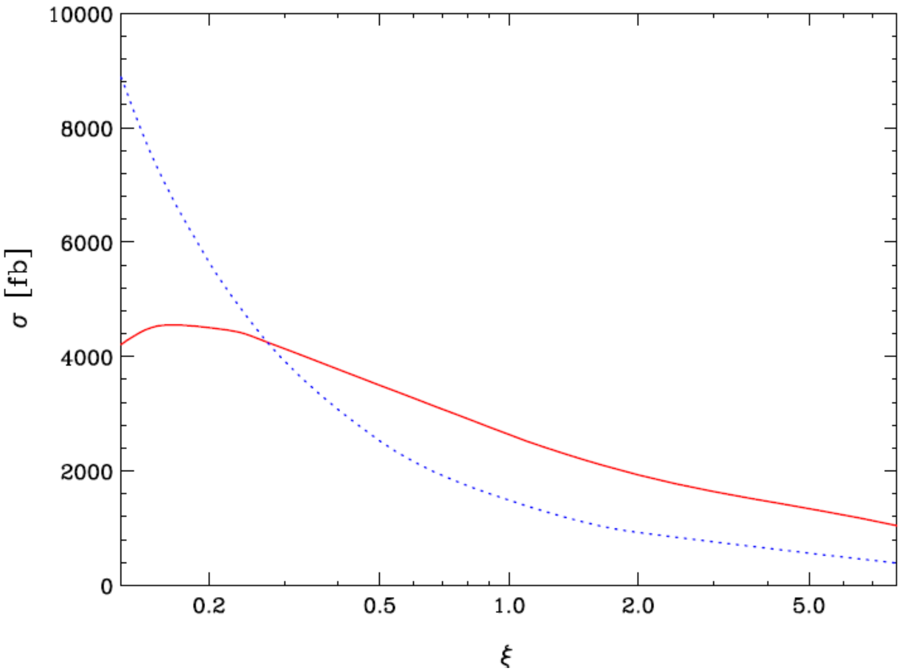
$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
σ^{LO} [fb]	8885(36)	2526(10)	1489.2(0.9)	923.4(3.8)	388.8(1.4)
σ^{NLO} [fb]	4213(65)	3498(11)	2636(3)	1933.0(3.8)	1044.7(1.7)

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

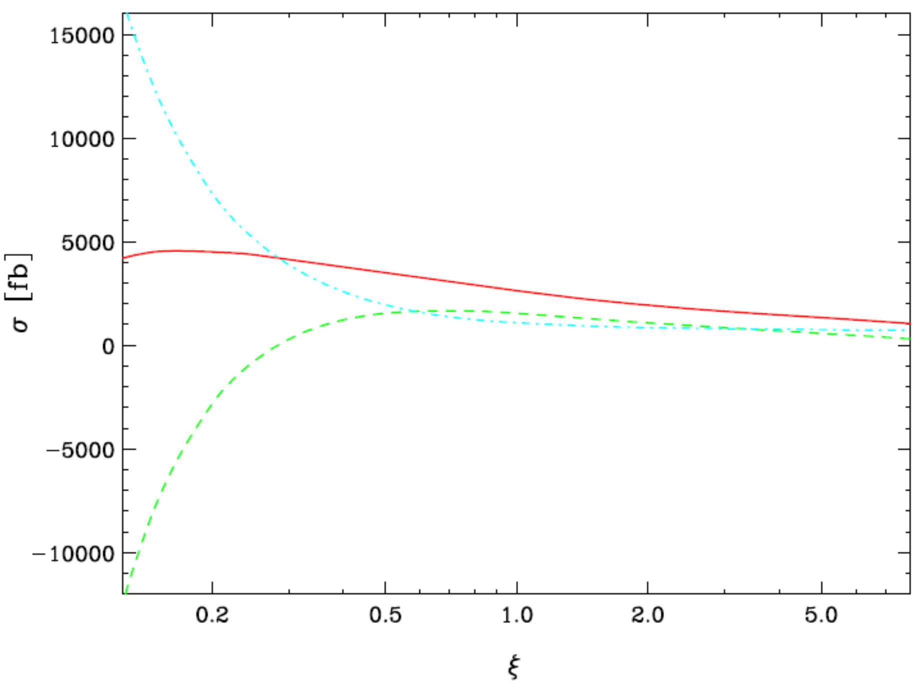
$$\sigma^{\mathrm{NLO}}_{t\bar{t}b\bar{b}}(\mathrm{LHC}, m_t = 176.2 \text{ GeV}, \mathrm{CTEQ6M}) = 2636 \;{}^{+862\ (33\%)}_{-703\ (27\%)} \text{ fb} .$$

- 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



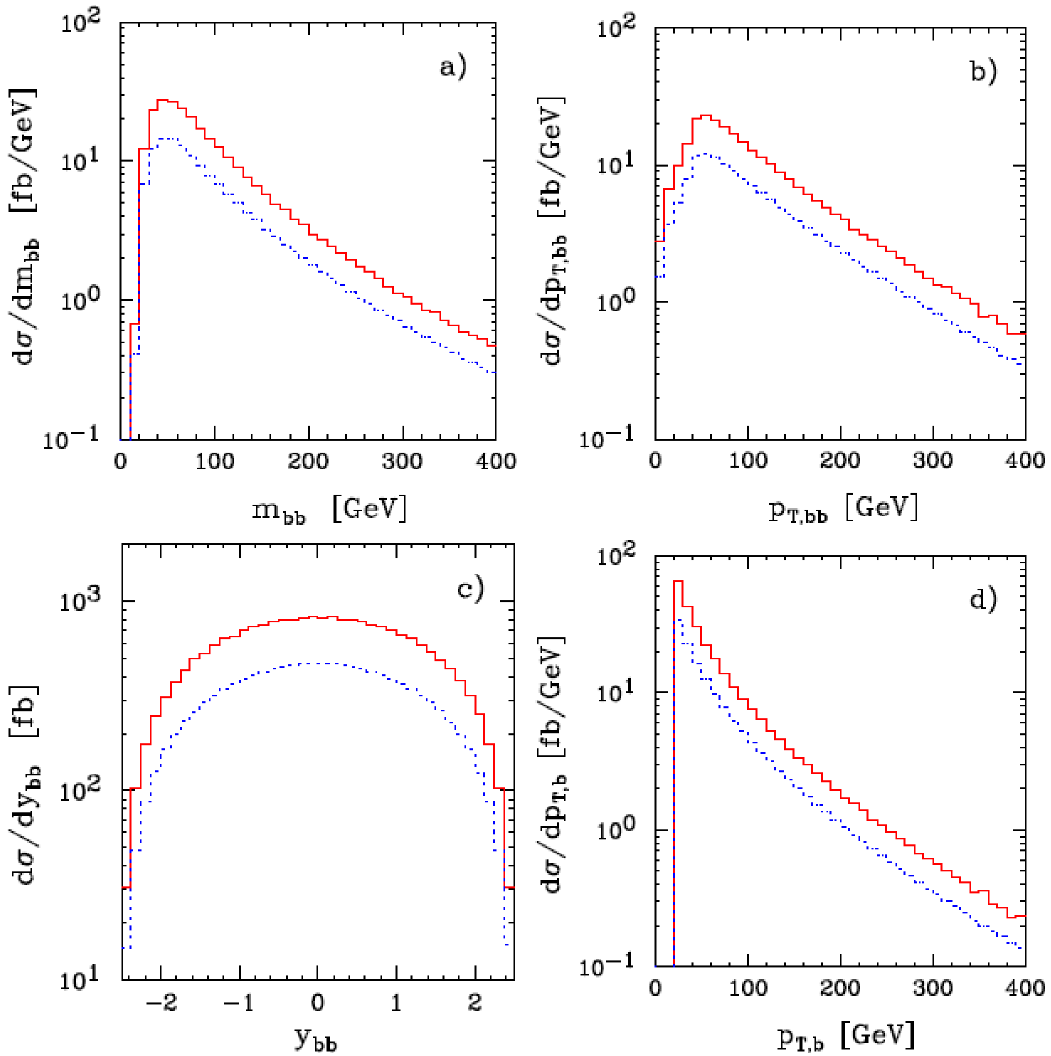
LO

NLO

virtual corrections

real radiation

Distributions



- 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

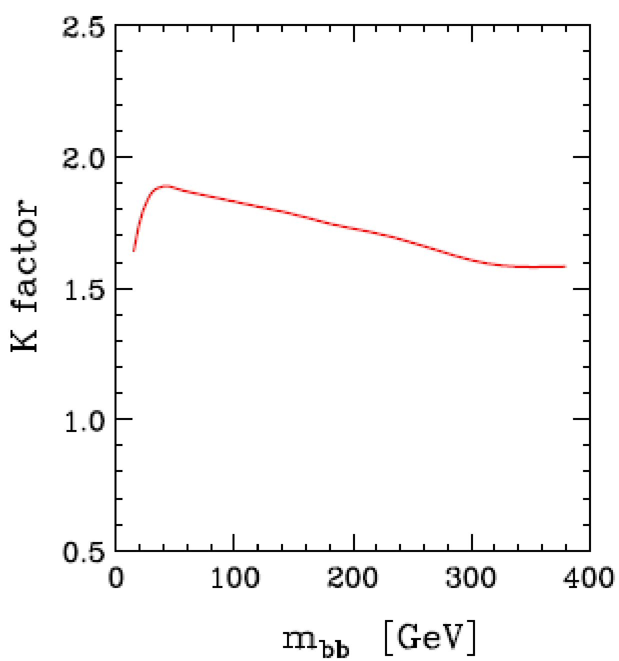
- LO
- NLO

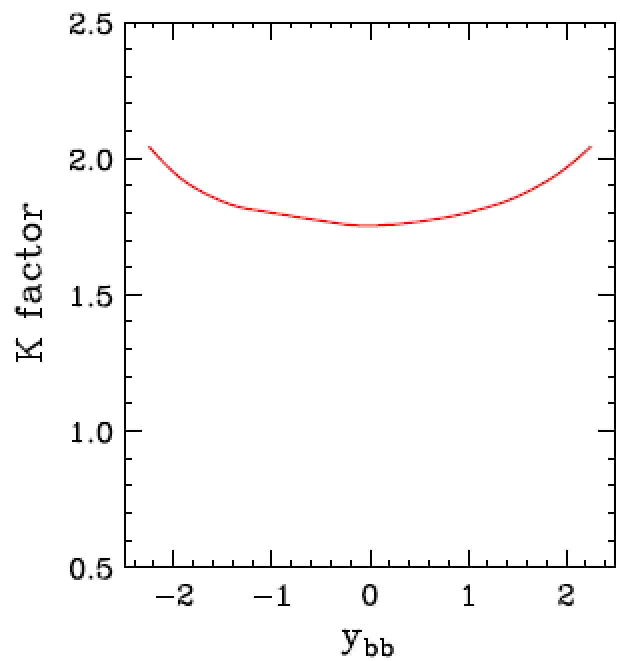
- All distributions for $\alpha_{max} = 0.01$
- Large corrections, relatively constant

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

- **HELAC–PHEGAS:** Framework for high energy phenomenology at LO + LL
- Automated approaches for NLO build around **HELAC-PHEGAS**
  HELAC-1LOOP, **CUTTOOLS** and **HELAC-DIPOLES**, **ONELOOP**
- First results have been obtained. More $2 \rightarrow 4$ processes in preparation
- Contribute to **ATLAS** and **CMS** generator groups in all stages (interfacing, validation, tuning, installation, configuration, user help, **physical analysis**...)
- Make **HELAC-PHEGAS** an option for the **LHC** !